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# AUTOMOTIVE ELECTRONICS

Traffic Management • Intelligent Control
Roadside Information • Vision Enhancement • Safety and Reliability

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## FEATURES



*Cover: Alexander Torres*

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# DEPARTMENTS



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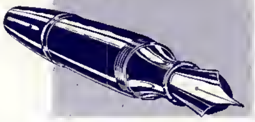
# From the Editor in Chief



## Check point two

IT IS TIME to check the balance sheets again: One more year of work has been accomplished, and we still have work to do and plans to make for the future.

For the electronic industry (as for many others), 1992 could not be classified as a "booming" year. While technology continued to produce more and more impressive results, companies continued to lay off people. This was a common denominator in the US and Europe last year, but now some hope of a trend reversal is appearing, at least in some areas.

These economic problems also impacted the life of technical publications, like our magazine. People have less time to write (unpaid) articles and to review those written by other authors. Subscriptions do not increase. (This last statement is formally correct, even if someone could say I express the situation from an optimistic point of view.) The Editorial Board and the editorial staff worked hard to keep *Micro* going through 1992, maintaining or improving the level of service provided to readers. You can judge whether we succeeded.

In particular, the efforts of managing editor Marie English and the use of new technologies at the Los Alamitos office allowed us to keep publication costs low. Low costs are critical in delivering the number of pages you are accustomed to—and even more to appreciate, since for much of 1992 the *Micro* editing staff went from two people on one magazine to one person on two magazines.

The main scope of *Micro* is to bring useful information to readers, but in our field the value of information decreases with time. Therefore, the efforts of the Editorial Board in reducing the review time of manuscripts submitted for publication continued in 1992. I am proud to say that the average delay from submission to acceptance (or rejection) is now around three months. Those of you who are familiar with technical publications can appreciate the value of this figure. Referees play a key part in the review process. Authors know how valuable are comments and suggestions from other experienced people. To acknowledge this work, each year *Micro* will publish the list of referees who contributed to the previous year's issues. We heartily thank each of the 1992 referees you will see listed here; they take time to see that *Micro* continues to be the well-received magazine that it is.

What plans do we have for the coming year? We plan to keep and increase our efforts at disseminating information that is useful to microsystems designers. We plan to place more emphasis on education (we are looking for good tutorial articles) and on standards. This last theme is a warhorse for *Micro* and is becoming more and more important as all markets become worldwide. Steve Diamond, the new editor for the Micro Standards department, will address the technical aspects and motivations, both of established standards and of the many efforts under way.

The application areas of microelectronics and microsystems are continuously expanding, and *Micro* plans its content to cope with this process. In 1992 you could read special theme issues on the latest microprocessors (Hot Chips issue), associative memories, a snapshot of the European microprocessor industry, video chips,



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and special signal processors. In 1993, besides this current issue on automotive electronics, you will be able to read about packaging and interconnections, plus the latest news from the Hot Chips conference, Far East industry, and standards. Plans for 1994 are under way. Be ready for hot themes like fault-tolerant systems, optical computing, intelligent sensors, and more.

This is what we can provide to readers, but we must also receive from them. What I feel is missing is more feedback. In electronics it is well known that positive feedback (in this case confirmation that what we are doing is correct) must be kept to a minimum to avoid instability. On the other hand, negative feedback (what you do not like, what we should change) is extremely important. Please continue to make proposals and suggestions on what to add, change, or cut; making *Micro* better and better is our goal and yours.

## Mailbag

(LK: liked; DLK: disliked; LTS: like to see)

**October 1991**

LTS: More detailed information about ICs and microprocessors.—V.D., Moscow

**February 1992**

LK: Am29000; LTS: DSP processors—M.E.M., Teheran, Iran [The December issue should fulfill your request.—D.D.C.]

LK: Neural network classifier; LTS: everything is OK; you are on the right path.—R.V.S., Ljubljana, Slovenia [Thanks; any suggestions for doing better?—D.D.C.]

**April 1992**

LTS: DEC Alpha; monograph on RISC.—P.P., Civitanova, Italy [RISC architectures are extensively covered in the Hot Chips special issues (February and June 1990, June 1991, and April 1992); DEC Alpha is coming.—D.D.C.]

LK: Micro Law (Nintendo v. Galoob)—D.S., Ottawa, Canada

LK: The R4000 and 88110 RISC reviews; DLK: not knowing what SPEC packages are used to benchmark these processors; LTS: these packages explained and Mflops rates in next review (also Linpack).—A.H., V.N., de Gaia, Portugal

LK: Motorola 88110 review and Mips R4000 processor.—S.D.K., Bandung, Indonesia

LK: Articles on RISCs; LTS: DEC's Alpha and NVAX RISC processors; DEC's Open Advantage and Open VMS.—J.F., Ljubljana, Slovenia

LK: MDP, R4000.—H.W., Bandung, Indonesia

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Micro View

# ICs per vehicle increasing rapidly

*Ware Myers*

*Contributing Editor*

The average number of integrated circuits per automotive vehicle is now 89, up from 70 only two years ago. These numbers characterize the growth rate of automotive electronic systems, Jerry Rivard, former chief engineer, electrical and electronics, for Ford Motor Company, said in an *IEEE Micro* interview. Rivard started out in automotive electronics in the mid-1960s in Bendix Corporation's Advanced Automotive Concepts Program and later became group director of engineering for the Electronic Fuel Injection Division.

"We had cars running then with headway control, antilock braking systems, and electronic fuel injection; but we were too early," he said. "It didn't begin to happen until the mid-1970s."

Rivard headed the team that put the first electronic fuel injection system on the Cadillac Seville in 1975. In 1976 Ford asked him to organize its electronic program, and for 10 years he was chief engineer. In 1986 he returned to Bendix (Allied Signal Inc.) as vice president and group executive of Bendix Electronics. Recently he has been a consultant in the field. He is a fellow of the IEEE and the Society of Automotive Engineers and a member of the National Academy of Engineering.

**Is there a difference in automotive electronic systems put on high-end cars and low-end vehicles?**

You generally find functional systems, such as engine and transmission control, antilock braking, and air bag, going across all cars. Manufacturers need these systems to meet regulatory requirements like emission reduction, fuel economy, or safety. Merely giving the driver some convenience, like antitheft, electrochromic rearview mirror, keyless entry, or an exotic entertainment unit, adds costs the average driver is not willing to pay.

**What is an electrochromic mirror?**

An electrochromic phenomenon on the mirror darkens the reflected light responding to sensed headlights of a car approaching from the rear. Then, instead of having to reach up to the mirror and snap a button, it dims the mirror automatically.

**What are the major electronic systems now found on cars?**

The engine control module controls the power train. The latest version controls both the engine and the transmission. Some cars have a module for electronic-hydraulic steering that changes the gain on the steering system. An antilock braking module is catching on quickly. Other examples include a diagnostic module for the air bag system and a central module for instrumentation.

**What do you see coming in the next two or three years?**

The biggest growth area is the antilock braking system and extensions of it, such as traction control. You might get one wheel stuck in snow, ice, mud, or sand, where it just spins, and the wheels with traction don't move at all. Traction control transfers the torque from the spinning wheel to the wheels with traction, enabling the car to move out.

Air bags are coming on very quickly. The safety value has been proven. They will be going across all vehicles by the mid-1990s, from high to low, both driver- and passenger-side.

**What is coming after that?**

There is a lot of work in the industry laborato-



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ries on headway warning or control. These systems emit a radar or light beam (lidar) ahead of the vehicle to sense an object you want to avoid. The early systems probably will just give the driver an audible alarm. A still more advanced system is radar speed control. It warns you of too rapid a closure rate with the car in front or of a car cutting in front of you. If you don't take action, it will close the throttle and start some braking effect.

A project at the University of California, Berkeley, is developing a system of this type with the objective of moving more traffic. On a stretch of freeway in San Diego they are running a string of 10 to 12 cars spaced about three meters apart. The lead car sets the pace. If there is any change, the system provides braking and steering functions on the following cars. The system would allow more throughput, safely on a crowded freeway.

One of the biggest problems, honestly, is not technical; it is the fear of liability. The manufacturer who creates a new technology worries about the risk of some unknown failure. With any complex system, you are going to have at least a few failures. Before a system goes out to the public in the automobile industry, it must be highly reliable.

**That leads us into questions of design. How did you go about introducing new technology?**

The first thing you have to understand about the automotive industry is that it has its own way of doing things. Automotive management is basically skeptical about new technology. Moreover, most of the engineers are mechanical and don't understand electronics.

I learned that you don't come in with ideas that are not well thought out. An idea on paper doesn't sell. You have to come in with something demonstrable. You have to reduce the new idea to practical practice. When you are putting a million cars on the road, you can't afford something that doesn't work well.

**Semiconductors weren't very reliable in the early days. I remember the Japanese made a big impression a few years later with more reliable chips.**

Yes, I had problems on the automotive side, and I had problems on the semiconductor side. At first the semiconductor people had no feel for the automotive business. When the first ICs came out, the markets in computers and the like were huge. From the time the semiconductor companies started an idea to the time it made profits was as short as a year. But the automotive industry is very slow moving. It takes five years from the time you accept an idea until you see it in practice.

Semiconductor executives who later became good friends like Bob Noyce and Gordon Moore of Intel saw the prospect of investing money with only a long-term payback. At the time they were making money on product ideas with a fast turnaround. I had to sell both sides. It took about 15 years.

**Where is the industry today?**

It has become pervasive. Semiconductor sales to the automotive industry are around $2.5 billion, forecast to go to $5 billion by the middle of the decade. Market analysts expect electronic system sales, now about $8 billion, to reach $24 billion by the year 2000.

**To get that kind of growth, you had to do something about reliability.**

In the early 1970s drivability was atrocious. Emission regulations were just coming in, and the engineers were trying to cope with them using conventional mechanical technology. As a result they were not getting performance. For instance, you might have to start and restart your car three times before you got out of your garage. Now, with the electronic systems, you don't even think about things like that. You turn the key and bang! The car starts and stays started.

You have to give credit to the Japanese. They saw the need for reliability, and they understood the fundamentals of it. In those days when we multiplied the component reliability numbers together, we ended up with system assembly figures that no one wanted to put in the car. Well, we eventually solved that problem with a lot of demanding, pushing, and cooperation. At the same time we had to control costs. The automobile industry is extremely cost-sensitive.

**As you put more microprocessors in cars, you must have been putting in more software, too. What did you do about software reliability?**

In 1978-80 we put our first digital ICs in vehicles. Up to that time we had only analog systems. We put software in the IC processors and ended up with huge software problems. Of course, the ICs of that period were unreliable, too. In test it was hard to tell if a problem was caused by hardware or software. Our ability to verify software in the actual installation was not good.

We gradually developed tools and methods that allowed us to check software. Today we don't see a lot of software problems.

**How did you get these 5-volt electronic circuits to operate reliably in the car's noisy electrical environment?**

Well, we had trouble with electromagnetic interference. We finally had to write a textbook on how to design ICs into this harsh environment, and how to interface the ICs to sensors.

Sensors, even today, are one of our biggest problems. They are the Achilles' heel of an electronic system. In the 1970s we had to use what was available from aerospace, but they had few cost constraints. We had to adapt the technology to our industry.

Sensors are still not as reliable as they should be. Most of them are overpriced by a factor of two. We don't have the accuracy levels that we need for the next generation of control systems.

**Do your systems operate independently, or are they bused together?**

Communications between processors are changing dramatically. It will help to look at how this field evolved. We have gone through three phases and are in the fourth phase now. The first phase was just putting electronic components like clocks and radios in the car—no connections between them. In the second phase we put in electronic subsystems that merely emulated the mechanical system that already existed. But the new system was not optimized; it didn't take advantage of the potential of electronic systems.

In the third phase we recognized that we were proliferating subsystems, getting endless complexity. We began to ask: How do you interface these systems? How do you share sensors and databases? How do you optimize them? How do you diagnose malfunctions? We were in the system-engineering phase.

For instance, wiring harnesses were getting out of control. If a car door had all the available controls, you could have 50 or 60 wires running into it—a bundle as big as your wrist. Difficult to build, package, and install reliably. Also costly. We had to move toward multiplexing.

If everybody multiplexed in their own way, we would end up with protocols that would be costly and difficult to service. So the Society of Automotive Engineers and the International Standards Organization formed committees—with Japanese participation—to standardize multiplexing.

You are not going to see the whole car multiplexed overnight. It is coming in only where needed to reduce the number of wires and connectors, to move data from one system to others that use it, or to share sensors. Multiplexing also improves your diagnostic capability. You can interrogate different systems from a central point, decide what is wrong, and show how to repair it. A sensor on the transmission, for example, tells you how fast the drive shaft is turning. You need that information for engine control and antilock braking.

**That transfers the complexity back into software.**

Well, there is a benefit to putting as much as you can into the software. It gives you flexibility in handling year-to-year model changes as you come to understand system needs better. It reduces the cost of making changes.

**You sound as if you had confidence in the industry's ability to write error-free software.**

Well, we have come a long way. One number I remember: The air bag system is 99.99999 percent reliable. That is the design value. Engine control, of course, is a lot more complex. The possibility of software errors or hardware failures is greater because the number of components is much larger.

**Engine control is like running a little chemical plant.**

Exactly. Not only that, but the speed of response is critical. We are up to 18 MHz on the engine control units, and the designers want higher frequency to give them better accuracy.

**You mentioned a fourth phase. What is it?**

It is where we look not only at the systems on the car but also at the larger system, that is, the road system or the infrastructure, that the car operates in. It is the phase the Intelligent Vehicle-Highway Systems researchers are studying.

## Reader Interest Survey

Indicate your interest in this department by circling the appropriate number on the Reader Service Card.

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Guest Editor's Introduction

# An Electronic Copilot in Your Car?

***Bernd Hoefflinger***

*Institute for Microelectronics Stuttgart*

Electronics in the car continues to be a much debated issue. Fascination about its potential on the one hand and concerns about its invisible inner workings on the other hand, together with the impact on individual safety and freedom of action, provide a challenge probably unparalleled in any other field of applied microelectronics. With over 500 million cars on the world's roads, we certainly stretch our imagination if we think that all these units one day may have airplanelike cockpits in them. Moreover, with this or just because of this comparison, everyone of us can instantly quote many good reasons why electronic road traffic will be much more complex than electronic flying.

Appropriately, in the area of cooperative civil technology research and development, no more complex projects have ever been conceived than Prometheus in Europe and IVHS in the United States. Prometheus stands for Program of European Traffic with Highest Efficiency and Unprecedented Safety, while IVHS is short for the Intelligent Vehicle-Highway System. The public sector at state, national, and international levels as well as industry, academia, and consumer groups continue to advance these programs, which present unprecedented challenges for cooperation in very complex networks of communication and coordination.

The strategic plan for IVHS in the US[1] gives us an impression of this unique scenario. Although IVHS as a consolidated program is only two years old, already more than 50 operational test sites are in place, and the projected expenditures for IVHS deployment in the US run beyond $200 billion over a 20-year period.

Prometheus was conceived in 1986 as a joint precompetitive research and development program by the European automotive industry in five countries: France, Germany, Great Britain, Italy, and Sweden. It now involves 18 car companies, many electronics and supplier companies, over 100 research institutes and universities as well as numerous consulting companies and public authorities such as those for transportation and telecommunications. In spite of its significance, the annual Prometheus budgets of about $100 million have been lean, with more than two thirds provided by the industry and one third by national ministries of research and technology. Road transport-related programs of the European Community like DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) supplement the effort, and, recently, numerous test sites have been established in Europe with partial regional, national, and European Community support.

In Japan, several major projects are under way: RACS (Road/Automobile Communication System), AMTICS (Advanced Mobile Traffic Information and Communication System), and recently VICS (Vehicle Information and Communication System).

**Table 1. Intelligent Vehicle Highway Systems benefits matrix (in percentages).[2]**
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| Benefits | Individual travelers | Fleet operators | Businesses | Government agencies | Society at large |
|---|---|---|---|---|---|
| Safety | 40 | 20 | — | — | 40 |
| Congestion | 30 | 20 | — | 20 | 30 |
| Environmental benefits | — | — | — | — | 100 |
| Energy conservation | 30 | 10 | — | — | 60 |
| Universal mobility and accessibility | 70 | 10 | — | 20 | — |
| Public transportation | 60 | — | — | 20 | 20 |
| Economic activity | 40 | — | 40 | — | 20 |
| Law enforcement | — | — | — | 30 | 70 |

Source: Sigmund Silber

The scope and the progress of these programs are so multifaceted that I've had to deliberately select a certain topical area to give a somewhat concise view in this magazine of the present state of goals and results.

What are the expected benefits of intelligent vehicle-highway systems? A matrix,[2] reproduced in Table 1, addresses the major issues of safety, congestion, environmental benefits, energy conservation, universal mobility and accessibility, public transportation, and economic activity. Prometheus displays a similar ranking when one considers its major European demonstration projects:[3]

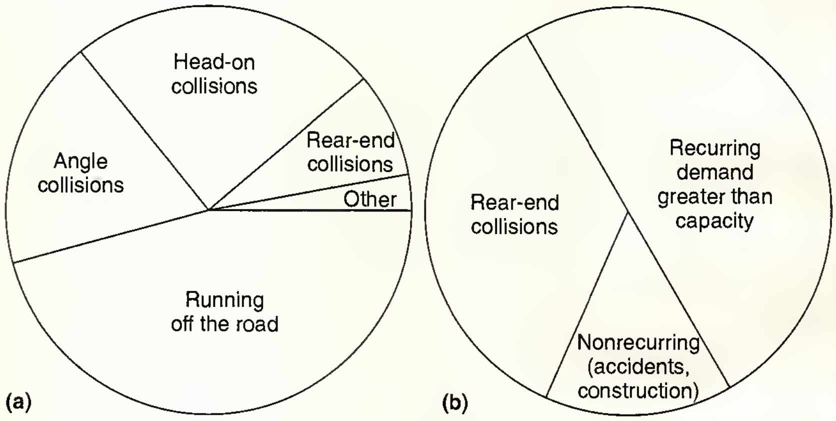


Figure 1. Causes of fatalities (a) and congestion (b).[1] *(Copyright 1992 Intelligent Vehicle Highway Society of America. Reprinted with permission.)*

- *Safe driving*
  Vision enhancement
  Proper vehicle operation
  Collision avoidance
- *Traffic flow harmonization*
  Cooperative driving
  Autonomous intelligent cruise control
  Emergency systems
- *Travel and transport management*
  Commercial fleet management
  Dual-mode route guidance
  Travel information services

The structure of IVHS again reflects this pattern with its five subprograms: Advanced Traffic Management Systems (ATMS), Advanced Traveller Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), and Advanced Public Transportation Systems (APTS).

The potential benefits from the view of the individual driver most likely focus on safety and mobility. The program areas of safe driving and traffic flow harmonization in Prometheus as well as Advanced Vehicle Control Systems in IVHS address these topics most closely. I've selected the articles in this issue of *IEEE Micro* accordingly.

A look at the causes of road traffic accidents and congestion (Figure 1) immediately shows the need and potential for significant improvements through the realization of what we colloquially call the electronic copilot in the car.[4] Over 90 percent

of all accidents in road traffic still result from human error.

Although the human brain's capacity for learning, association, memory, and processing far surpasses any computer conceivable at present, it is decidedly slow. The human reaction and decision cycle takes about 2 seconds, which is equivalent to traveling 50 meters in high-speed road traffic. Delays and errors in braking, passing, negotiating obstacles or curves, or recognizing signs and signals result in a presently unavoidable toll of accidents. Advancing the reaction time by just 1 second would eliminate 80 percent of these accidents.

Fatigue, misjudgment of safety margins, and incomplete knowledge of the status of our own vehicle and of other participants and objects in our relevant road traffic zone are the other major reasons for accidents and congestion. These causes indicate that significant benefits can and will only be possible if the electronic copilot in our car can communicate with other traffic partners, with the roadside, and with the travel management system.

Clearly, this scenario of road traffic differs considerably from what we have today, and it will take the cooperation of all constituencies to move into this new era. However, two major forces may bring about change:

- congestion and pollution approach total deadlock faster than present relief programs can affect, and
- big opportunities exist for the world's advanced economies to serve their citizens in the need and desire for safe individual mobility.

In the first article, "Research and Development Needs for Advanced Vehicle Control Systems," Steven Shladover of the University of California, Berkeley, who is also chair of the IVHS Advanced Vehicle Control Systems committee, identifies what must be accomplished in the new control systems. The second article presents an exemplary realization of an integrated system: the Arena public road test site in West Sweden. Its author, Ulf Palmquist of AB Volvo, is a deputy member of the Prometheus Steering Committee and chair of the Technical Board of the Swedish Road Traffic Informatics Program.

Given this scope of road traffic electronics, it is evident that mainstream microelectronics will not directly qualify for the car control functions, which are all safety-relevant. Car control electronics must have

- avionics reliability,
- no box protecting it from the environment,
- small volume and weight like a pocket computer, and
- lower cost than individual consumer electronics.

Among all these design and manufacturing challenges, microelectronics reliability is most important. Accordingly, reliability research has been a common thread in the Prometheus PRO-CHIP (Prometheus Custom Hardware for Intelligent Processing) subprogram, a basic research program in which over 40 institutes in France, Germany, Italy, and Sweden participated. Enrico Zanoni of the University of Padua, Italy, who has been the European lead researcher on reliability in PRO-CHIP and who has also been instrumental in establishing the reliability laboratory at the national institute CSATA, Bari, Italy, summarizes these activities in his article, "Improving Reliability and Safety of Automotive Electronics."

Advanced vehicle control systems will benefit from any imaginable development of new hardware and software with a special quest for robustness and cost. I've chosen two examples to indicate feasible solutions. Vision enhancement in fast-changing traffic scenes is possible with a high dynamic-range, random-access silicon camera. This is a prerequisite in a system for longitudinal and lateral car control. Given that support, it is still an intricate task to mimic the steering behavior of an alert driver. The concluding article describes a trained digital neurocontroller that serves as the steering assistant in a Mercedes car, which is under continuous test in normal road traffic.

Any view of car control systems presently under development or test should conclude with the comment that the deployment of these systems will be characterized by three stages to be accomplished over the next 20 years:

- advice and warning systems,
- support systems, and
- control systems.

IN THE SPIRIT OF THE UNIQUE COOPERATION in electronic road traffic as a significant civil technology research and development program, I must thank the many experts for their support. Special thanks go to the authors and the reviewers of the articles in this issue. I gratefully acknowledge the members of the European Steering Committee of PRO-CHIP and their contributions. They represent the many helpful scientists in Prometheus: Gianni Conte, Parma, Italy; Daniel Estève, Toulouse, France; and Peter Weissglas, Stockholm, Sweden.

## References

1. *Strategy Plan for Intelligent Vehicle-Highway Systems in the United States*, IVHS America, 1776 Massachusetts Ave. NW, Suite 510, Washington, DC 20036, May 1992.
2. "Public and Private Sector Roles in Intelligent Vehicle-Highway Systems (IVHS/Deployment)," *Proc. Seminar Federal Highway Administration*, No. 1992-625-205/60497, US Government Printing Office, Washington, D.C., Apr. 1992.

3. "Prometheus 'Safe and Effective Mobility in Euorpe'," Prometheus Office, Postfach 600 202, D-7000 Stuttgart 60, Germany, Sept. 1991.
4. B. Hoefflinger, "Computer-Assisted Motoring," in *Scientific Europe*, N. Calder, ed., Nature & Technology Scientific Publishers Ltd., Maastricht, Brüssels, and London, 1990, ISBN 90-73035-06-6/CIP, pp. 28-33.



**Bernd Hoefflinger** is director of the Institute for Microelectronics Stuttgart, which develops, manufactures, tests, and qualifies application-specific microchips for industrial applications. He is also in charge of the electronics manufacturing program at the University of Stuttgart. Earlier, he worked as a scientific staff member and as the founder of the MOS Integrated Circuits Division for Siemens AG, Munich. He has held faculty positions with the Electrical Engineering Departments at Cornell University, Ithaca, New York; the University of Dortmund, Germany, as founder and head; the University of California, Berkeley, on a sabbatical; and the University of Minnesota and Purdue University, Indiana, as head. For the Prometheus Eureka Research Program, he serves as the European coordinator of the basic research program, "Custom Hardware for Intelligent Processing" (PRO-CHIP).

Hoefflinger received his diploma degree in physics from the University of Göttingen and his PhD degree from the Technical University of Munich.

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## Reader Interest Survey

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# Research and Development Needs for Advanced Vehicle Control Systems

**The Advanced Vehicle Control Systems Committee of the Intelligent Vehicle Highway Society of America has identified research and development activities necessary to improve the performance of the surface transportation system. AVCS represent the application of sensors, computers, and electromechanical actuators to provide drivers with warnings of hazards, assistance in controlling their vehicles, or fully automated control of vehicle motions.**

***Steven E. Shladover***

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During the middle 1980s, transportation planners and researchers realized that the rapidly worsening problems of the road transportation system would not be addressed adequately, much less solved, by continued reliance on conventional technologies. This realization grew separately among public agency officials, automotive industry managers, and academic researchers in Europe, North America, and Japan. The interested parties on each continent organized themselves to conduct research, development, and demonstration programs on somewhat different time scales and with somewhat different emphases. These activities have come to be known variously as Intelligent Vehicle-Highway Systems (IVHS) in North America and Road Transport Informatics or Advanced Transport Telematics in Europe. This jargon is not particularly helpful to understanding. A more appropriate term would simply be "Intelligent Transportation Systems."

The unifying themes among these activities are the application of information technologies to the operation of road transportation systems in a much broader fashion than ever before, and the integration of travelers, vehicles, and roadway infrastructure into a comprehensive system by use of the newly available information. Such applications of information technology are relatively commonplace in the air, rail, and marine transportation domains today. However they are extremely rare in road transportation, despite the dominant role that rubber-tired transport maintains throughout the industrialized world.

In North America an ad hoc group of academic, government, and industry people, who met periodically from 1988 to 1990 under the name of Mobility 2000, defined the basic outlines of IVHS. This effort began with a group of about 40 people meeting at the University of California, Berkeley, in March 1988 and concluded two years later with a meeting attended by several hundred participants in Dallas. Mobility 2000 was succeeded by a more formal organization called the Intelligent Vehicle Highway Society of America (IVHS America), which was chartered in 1990. This group has prepared a strategic plan for the development and deployment of IVHS in the US, which has been followed by more specific near-term program recommendations to the US Department of Transportation.

The goals of the IVHS program are to improve the performance of the surface transportation system in a wide variety of dimensions by

- reducing traffic congestion;
- improving safety;
- enhancing mobility of travelers, especially the elderly and disabled;
- increasing the productivity of the transportation infrastructure;
- reducing energy use;

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**AVCS can provide warnings to the driver, assist in controlling the car, and even take complete control of the car's movements.**

- reducing pollution;
- reducing capital and operating costs;
- increasing the viability of public transportation;
- responding more effectively to incidents; and
- increasing the ease and convenience of travel.

These goals should all be promoted by the use of IVHS technologies.

Inherent to the concept of IVHS is the use of information to link the traveler, vehicle, and roadway infrastructure as an integrated system. This means that new organizational and managerial approaches will be necessary to lead to deployment and operation. The technological linkages cannot be accomplished unless the private developers of vehicles and in-vehicle technology, the public owners and operators of the roadway, and the commercial and individual travelers work together to decide what they need and how to achieve it. The political, organizational, and managerial efforts associated with this coordination across sectors are likely to be as challenging as the technology development efforts needed to bring IVHS forward to deployment.

The IVHS program in the US has been subdivided into six functional areas, three of which are oriented toward the following families of technology: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), and Advanced Vehicle Control Systems (AVCS).

Three functional areas are oriented toward application domains: Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS), and Advanced Rural Transportation Systems (ARTS).

A technical committee in IVHS America represents each of these functional areas, with cross-cutting committees in a variety of other areas:

- Systems Architecture,
- Safety and Human Factors,
- Standards and Protocols,
- Institutional Issues,
- Legal Issues, and
- Benefits, Evaluation, and Costs.

IVHS, including its most advanced element, AVCS, is by no means a creation of the most recent decade. The concept of automating traffic flows was portrayed as part of the General Motors Futurama exhibit at the 1939-40 New York World's Fair. General Motors and RCA tested some of the technology of vehicle control on experimental vehicles in the 1950s and 1960s,[1] and analogous experiments were also conducted in Japan[2] and England[3] prior to 1970. Ohio State University conducted an extended program of automated highway research in the 1960s and 1970s under the leadership of Robert Fenton.[4]

In the late 1960s and 1970s, the interest in automatic control of rubber-tired vehicles shifted from the application on private passenger cars to transit operations on exclusive guideways, known as Personal Rapid Transit (PRT) or Automated Guideway Transit (AGT).[5-8] Hybrid automated vehicles, capable of operation both on guideways and conventional roads, became known as Dual Mode.[9] Research results obtained on all of these developments are scattered widely throughout the technical literature, with the heaviest concentrations of papers in the conference proceedings just cited. The *IEEE Transactions on Vehicular Technology* published three feature issues highlighting IVHS and AVCS technologies, scattered at about 10-year intervals.[10-12]

In the present-day IVHS program, the strongest emphasis has been placed on the nearer term technologies of ATMS and ATIS, with considerably less attention having been paid to AVCS. This emphasis is reflected in the principal IVHS conference proceedings of the past several years,[13-18] which have very few if any papers about AVCS. Some of the current AVCS technology research has been reported in a handful of sessions at the three most recent American Control Conferences.[19-21]

We can now focus on the AVCS and the technical issues that the AVCS Committee has identified as needing attention.

## Advanced Vehicle Control Systems

AVCS represents a broad grouping of technologies and potential products, not all of which are control systems. This category includes not only systems that can take complete control of the movements of a vehicle but also systems that can assist a driver in controlling the vehicle and systems that provide "high-bandwidth" information to the driver, particularly about imminent hazards. AVCS therefore subdivide into three separate stages of development, which are expected to follow increasingly long (but still somewhat overlapping) development paths:

- driver warning and perceptual enhancement systems,
- driver control assistance systems, and
- fully automated vehicle control systems.

At each stage, AVCS involve interactions among different

vehicles or between vehicles and the roadway infrastructure. The fully automated vehicle control systems, such as the automated highway systems (AHS), are particularly controversial because of their significant difference from present-day operations. Opinion within the IVHS research community and the larger transportation community differs regarding the feasibility, desirability, and time scale for their development and deployment. While some observers concentrate on the potentially very large benefits in safety, capacity, and efficiency that AHS could offer, others concentrate on the technical and institutional risks to overcome and the up-front investments that will be needed to realize those benefits.

Many enabling technologies will be applicable to each of the three stages of AVCS development, and should therefore not be assigned to any one of the three individually. Each stage will have its own target products that will be made available to the public for use. Some of these individual products can be combined to produce more comprehensive systems, with a wider range of public and private benefits. The AVCS subject area has been subdivided according to each of these three dimensions (enabling technologies, target products, and systems) for study. Different kinds of activity need to be associated with each.

The activities needed for enabling technologies include

- definition of performance requirements,
- identification and evaluation of promising existing technologies,
- identification of "gaps" in available technologies,
- basic research and development on needed technologies, and
- adaptation of existing technologies to AVCS needs.

The target products need

- definition of performance requirements;
- selection of enabling technologies to use;
- product design, development, testing, and marketing.

The systems will need

- definition of performance requirements,
- concept design and analysis,
- selection of target products to incorporate,
- research and design of system architecture, and
- coordination of public and private sector roles.

Here, the principal focus is on the enabling technologies, which can serve as the building blocks for development of the products and systems. These are also likely to be more familiar to readers who are not yet well versed in the subject of IVHS. Later I discuss briefly the products and systems in which these technologies will be used.

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## Enabling technologies for AVCS—Constraints

Subdividing the enabling technologies for AVCS into several common groups eases discussion. These groupings are not entirely distinct from each other, but must be related.

The hardware technologies are generally not very exotic by standards normally encountered in the aerospace, defense, or computer industries. However, it is essential to recognize the strong constraints under which these technologies must be brought to maturity for successful use in AVCS. These are primarily cost, reliability, fault tolerance, and environmental hardening, combined with the basic performance requirements.

**Cost.** The automotive world is extremely price sensitive. Automotive OEMs take pains to squeeze every penny of avoidable cost out of a vehicle or option, and every dollar of additional unit cost requires major justification. Complete AVCS must be sellable to the end user for several hundred dollars, and probably an absolute maximum in the range of $1,000, according to the currently accepted thinking within the US automotive industry. This factor imposes much more severe unit cost constraints than the aerospace or defense industries are accustomed to. If suitable technological approaches are considered from the start, significant production economies of scale should be expected when yearly sales are in the hundreds of thousands or millions. However, the unit costs and mass production volumes must be considered carefully right from the start.

**Reliability and fault tolerance**. All AVCS devices have significant safety implications for the equipped vehicles, their occupants, and their neighbors. If they malfunction, they can easily produce accidents, with property damage, injuries, and even fatalities. The existing road transportation system, even with its unacceptably high accident rate, is actually characterized by remarkably high mean times between fatalities and injuries. Recent US traffic accident statistics indicate a mean time between fatalities (MTBF) on the order of one million vehicle hours for all classes of roads, and even higher than that for limited-access freeways. Even if a failure is taken to represent an injury-producing accident, the MTBF is still on

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the order of tens of thousands of vehicle hours. These are remarkably high reliability levels to be achieved by complex technologies. Since one of the primary IVHS goals is improving safety, it will be necessary for AVCS devices to exceed these current effective reliability levels.

The need for very high effective MTBF in the complete system indicates the need for both high reliability and fault tolerance in component and system designs. This factor has implications for both hardware and software designs. It also reinforces the need for extremely low unit costs of components so that the most critical ones can be used redundantly or with voting (selection of majority sensor readings) to enhance system reliability.

**Environmental hardening.** The environment in which automotive equipment must operate is quite inhospitable. It includes wide ranges of temperature and humidity, substantial noise (acoustic and electromagnetic), vibration, as well as dust, dirt, snow, ice, fog, and other adverse weather conditions. Because of the safety-critical character of much of the AVCS equipment, it really must be able to operate effectively under all possible combinations of adverse environmental conditions, probably even up to a nearby lightning strike, but stopping just short of thermonuclear war or a major hurricane or tornado.

## Needed technologies

The enabling technologies for AVCS have been subdivided into categories of sensors, communication, computation, electromechanical actuators, software and systems technologies, and special tools and facilities.

**Sensors.** The largest and most important single category of needed enabling technologies is sensors to detect the condition of the vehicle and its driver, as well as its location relative to the roadway and other vehicles. The following kinds of sensors are likely to be needed:

- *Ranging devices to detect the spacing and velocity difference between a vehicle and its neighbors, both fore, aft, and to the sides.* The required range is likely to be between 1 and 100 meters, with an accuracy of 1 percent, a sampling rate of at least 20 Hz, and the ability to operate under all weather conditions.
- *Obstacle detection to find hazards in the vicinity of a vehicle so that accidents can be avoided.* These sensors share some of the requirements of the ranging devices but must also be able to distinguish objects other than vehicles. The objects could be people, animals, dropped loads, and other objects sufficiently massive to cause damage to the vehicle if they are hit. On the other hand, the range accuracy needed for this function is probably significantly less than that required for the ranging used in vehicle-following control.
- *Lane sensing to detect the lateral position of a vehicle relative to the center of the lane.* The required range is likely to be up to one full lane width, with an accuracy of 1 cm for small deviations and perhaps 10 cm for large deviations.
- *Vision enhancement to produce an image of the environment ahead of a vehicle.* These sensors enable drivers to see obstacles, other vehicles, their own position in the lane, or any other pertinent items that they would otherwise be unable to see because of darkness, glare, dust, or precipitation. The sensor system must have a range of a few hundred meters under all environmental conditions, with high enough resolution to pick up all relevant hazards. They must also be combined with a compatible display to supply the image to the driver with sufficient resolution, contrast, and brightness.
- *Road friction sensing to measure in real time the coefficient of friction between the tires and the road surface.* The vehicle control systems can then respond appropriately to rapid changes in road conditions (snow, ice, standing water, sand, oil).
- *Absolute location sensing to detect the location of a vehicle along its path, relative to entry and exit points or other mileposts.* If this is to be used only for routing purposes, the accuracy could probably be 10 meters. However, if used to determine locations of vehicles relative to each other for regulating maneuvers, the accuracy will need to be better than 1 meter.
- *Absolute velocity vector of the vehicle, not sensitive to tire slip or loss of traction.* This system would determine magnitude and direction, so that longitudinal and lateral components of motion can be distinguished.
- *Accelerometers to accurately measure (perhaps 1-percent errors) vehicle longitudinal and lateral accelerations, compensated for road geometry effects such as grades and superelevations.* These measurements are needed to enhance the performance of the vehicle control systems and to provide redundancy for other measurements of the vehicle state.

- *Angular rotation rate to measure yaw rate in particular, a very useful measurement for vehicle lateral control.*
- *Linear displacement measurements of suspension deflections and steering system motions to verify that the vehicle responds to commands in the correct way.*
- *Driver performance to identify the alertness of drivers and their ability to control the vehicle safely.* This has two different uses, one to provide a warning to drivers if their performance is degrading while driving and the other to verify the readiness of drivers to resume manual control after the vehicle has been operating under fully automatic control.

**In fully automated systems, the vehicle-roadway communications are also vital for system management, routing, and scheduling functions.**

**Communication devices.** This category includes vehicle-vehicle and vehicle-roadway communications.

Vehicles can alert their neighbors within the same and adjacent lanes through short-range, line-of-sight, two-way, full-duplex communications. These communications are needed for coordinated control and maneuvering and to warn of immediate dangers such as obstacles or vehicle failures. They need to be relatively fast, with high bandwidth and extremely high reliability under all conditions.

Vehicles can also use two-way, short- to medium-range communications between themselves and the roadway. Depending on the system design and operating concepts, these may require any of a wide range of capabilities. In particular if these are substituted for any of the vehicle-vehicle communication needs, the requirements will be substantially more demanding than they would otherwise be. Regardless of the use of vehicle-vehicle communications, this function is still needed for supplying system-level control information to vehicles and for notifying the system of any problems that occur on board the vehicles, as well as for passing information between vehicles that are out of each others' sight or communication range. In fully automated systems, the vehicle-roadway communications are also vital for system management, routing, and scheduling functions.

**Computational devices.** All of the vehicle control functions require processing of sensor data and calculation of control actions (commands to actuators or driver displays). These devices can require a wide range of computational capability. The performance requirements are therefore more uncertain than any of the other enabling technology requirements. For example, if machine vision is chosen as the preferred sensing mechanism for some functions, the computational requirements are likely to be significantly greater than they would be for alternative sensors. The primary issues remain high reliability, low cost, and robustness in all environmental conditions.

**Electromechanical actuators.** The control assistance and fully automated AVCS functions require means for implementing the control actions, to change the speed or direction of motion of the vehicle. This involves actuation of the engine (throttle), brakes, and steering system. Some of the enabling technologies are already in use on present-day vehicles. These can range from the antilock braking systems that are now widely available to the traction control and four-wheel steering systems that are only available on a relatively few sophisticated automobiles.

Electronic braking control involves full-authority control of the braking effort, ranging from no braking to full emergency braking, with very fast response. This function extends beyond antilock braking, which can only modulate the braking effort initiated by the driver. While the control signals would be electronic, the actual braking effort would probably be hydraulic, under control of an electrohydraulic servo valve.

Electronic engine control involves full-authority control of engine throttle and fuel injection, with very fast and accurate response to changes in commanded engine torque or speed. This function extends beyond traction control, which can only modulate the engine commands initiated by the driver. It is only available today at very high cost on a limited selection of automobiles, in which the driver's accelerator pedal commands are translated into electronic commands to the engine.

Electronic steering control involves full-authority control of the steering angle, with fast and accurate response to commanded steering changes. While the steering control signals would be electronic, electric or hydraulic actuation systems could turn the wheels. Limited subsets of this capability steer the rear wheels of a few current automobiles that offer four-wheel steering.

**Software and systems technologies.** Even when the basic hardware is available to meet some of the needs of AVCS, software must still be developed so that the hardware functions as needed. This is likely to be the most labor-intensive part of the development activities, as well as the most heterogeneous. Some of the work occurs at the microscopic level within the system, while other work ranges all the way up to the most macroscopic level.

- *Reliable, fault-tolerant system designs.* The combination of hardware and software to produce highly reliable and

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fault-tolerant systems within tight cost constraints will be one of the most challenging topics in all of IVHS. Although substantial effort has been devoted to design of highly reliable and fault-tolerant systems in the aerospace, nuclear, computer, and process control industries, these application domains have not been as cost-intolerant as the automotive-IVHS domain. Extremely high MTBF rates will be needed in complicated electromechanical systems that can be sold for less than $1,000. The cost constraints may produce the need for some significantly new approaches in this arena.

- *Fault detection and accommodation.* All major subsystems within the automobile should have self-diagnostic capabilities, combined with fall-back modes of operation to accommodate faults. While some diagnostics are already being applied on a "static" basis to facilitate troubleshooting by automotive maintenance people, this software will need to be extended to on-line diagnostics, combined with the logic to choose the most appropriate "degraded" mode of operation. Development of these capabilities will require fairly basic work on fault-detection logic, combined with very practical consideration of the implementation means available on automobiles.
- *Data fusion.* AVCS vehicles will be equipped with many sensors, incorporating substantial redundancy to achieve the reliability and fault tolerance goals. Substantial attention must be paid to the design of the data fusion software. This software will combine the outputs of the various sensors with their different accuracies, error characteristics, and failure modes. When the sensors produce seemingly incompatible outputs, the software will have to define how heavily to weigh the competing information to produce a high-confidence estimate of what is really happening.
- *Threat analysis.* The road environment can be remarkably complicated, particularly if no special measures are taken to simplify it for the benefit of automated vehicles. Thus it will be very challenging for vehicle-mounted sensors to interpret the information they receive so that they can distinguish genuine threats from spurious ones. For example, the sensors will have to identify how threatening an oncoming vehicle is on a curving two-lane rural road: Is it staying in its own lane, or is it straying into my lane? It can also mean predicting whether a vehicle crossing in front of my vehicle is likely to collide with my vehicle, or whether the animal on the road in front of me is a bird that can fly away before I hit it, my neighbor's cat, which I should try to avoid hitting, or a squirrel, which I may not mind hitting. These examples are specific cases, which will each require its own logic. This topic is likely to be complicated precisely because of the large number of such examples that will need to be considered.
- *Nonlinear and adaptive control design.* Automotive vehicles are highly nonlinear, and their precise performance characteristics depend on many difficult-to-predict variables. Therefore, nonlinear and adaptive control systems must control these variables consistently, reliably, and with high performance. The theory for design of such systems is still in its relative infancy. Substantial research will be needed to develop control software that can successfully handle the full range of conditions that each vehicle will encounter throughout its useful life. Included are the normal aging of components and subsystems, substandard maintenance, and substantial variations in loading, as well as variability in the weather and road surface conditions.
- *Human interface designs.* AVCS can substantially change the experience of driving in a variety of ways. Interactions between the driver and the vehicle must be understood thoroughly before AVCS-equipped vehicles are made available for public service. In the case of the driver warning and assistance systems, designers must understand how drivers will react to the different kinds of information and control assistance that will be offered, so that the safety and effectiveness of the system are not compromised by unintended human responses. They must also understand what the drivers like and dislike about various aspects of these systems, so that the systems will be sufficiently attractive for people to want to buy them.

The human interface issues are somewhat different for the fully automated systems, since these represent even more dramatic departures from present-day driving practices. In this case, designers must understand how drivers respond to relinquishing control of their vehicles to the automatic systems, and what performance or operational characteristics of the automatic systems make them more or less attractive to people. We need to understand how much, and specifically what, information drivers want to receive about the operation of their vehicles when they are driving in the automated

mode. The return of control to the driver at the end of the automated stage of a journey also needs significant attention, particularly to establish how to verify that the driver is indeed sufficiently alert to drive safely.

- *Automatic trip routing and scheduling.* Fully automated driving offers the possibility of automatic routing and scheduling of trips to make optimal use of the automated road network. Substantial software work will be needed to develop and refine the routing and scheduling algorithms. These algorithms should permit the simultaneous optimization of individual vehicle paths and network flows in systems that may contain hundreds of thousands of vehicles at a time.
- *Architecture for system integration.* Each stage in the development of all IVHS functions involves making decisions about the distribution of intelligence within the system. AVCS is no different from the rest of IVHS in this need. Defining the most suitable system architecture is a challenging effort because of the multitude of considerations that must be weighed.

  Depending on how intelligence is allocated among individual vehicles, groups of vehicles, local roadside installations, and a central roadside installation, the communication burdens can vary substantially. The costs of the communication must be weighed against the costs of the information storage and processing elements at each location. Designers must take into consideration as well the need for system-level reliability and fault tolerance. All of this must also take into account the varying possible rates of market penetration of vehicle equipment and installation of roadside equipment, which are financed by different sectors of society. The combination of issues such as these imbues the architecture problem with its richness.

**Special tools and facilities.** The development of AVCS technologies will require the availability of a substantial amount of data, models, facilities, and vehicles that do not generally exist. The time and resources required for acquisition of these special needs must be taken into account in planning the development of AVCS.

- **Data**. Considerable data about current conditions are needed to provide a solid foundation upon which to build the designs of new AVCS intended to help solve today's problems. These include several different categories of data.

  *Accidents.* Extensive information about the causes and mechanisms of accidents is needed. The AVCS can be targeted at avoiding the most important and serious types of accidents. In addition, authoritative information about the impacts of accidents on congestion helps in estimating more accurately the benefits of accident reductions.

**We need to understand how much, and specifically what, information drivers want to receive about the operation of their vehicles when they are driving in the automated mode.**

  *Vehicle characteristics.* Dynamic responses of vehicles, including variations with respect to aging and inadequate maintenance, will allow control systems to be designed to satisfy the full range of needed performance.

  *Driver characteristics.* Comprehensive information about driver responses to the variety of stimuli that can be provided by AVCS warning and assistance systems will allow these stimuli to be selected most appropriately.

  *Road characteristics.* The complete range of road geometry and surface conditions in which the AVCS are expected to operate will be combined with the complete range of weather conditions that must be accommodated.

  *Component reliabilities.* Statistically valid data are needed about the reliabilities of components currently used on automotive vehicles and the components proposed for use in the AVCS.

  *Traffic flows and demand.* Transportation planning data are needed to indicate the level of demand that systems must be designed to service.

- **Models.** Data of the type just indicated must be used to develop models that can predict the performance of AVCS at several different levels, from the driver-vehicle interaction to the operation of a complete regional transportation network. They include

  - driver behavior and driver-vehicle interactions,
  - vehicle dynamic response,
  - transportation networks and traffic flows,
  - benefits evaluations, and
  - protocols for evaluation of experiments and operational tests.

- **Facilities**. Large-scale test facilities are needed to evaluate and then demonstrate the performance of AVCS be-

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fore these are sufficiently mature to be used in mixed traffic on public roads. The driver warning, perceptual enhancement, and control assistance systems can probably be tested on existing automotive test facilities, in the same ways that other new automotive systems are tested. However, the fully automated systems will require special facilities, with cooperative infrastructure elements installed in, or adjacent to, the roadway. These special facilities must be of sufficient scale to represent the full range of driving conditions that could be experienced in an automated roadway facility, including multiple lanes of traffic, interchanges with local streets, and freeway-to-freeway interchanges.

- **Test vehicles.** Substantial fleets of test vehicles must be equipped with the AVCS technologies. They will make it possible to accumulate enough vehicle hours of operation to prove satisfactory performance under all reasonable combinations of operating conditions and to prove adequate reliability.

  In addition, demonstration of fully automated operations will require the use of a substantial number of vehicles. The number must be sufficient to prove the absence of undesirable interactions among the automated vehicles and at the same time demonstrate the extremely high travel densities that these systems are intended to achieve. All test vehicles will need to have sufficient instrumentation to record experimental results of interest (especially any abnormal conditions or failures).

## AVCS target products

The enabling technologies are not ends in themselves, but they are the means for implementing products that can be used by travelers. Certain target products motivate the development of the enabling technologies.

- Driver warnings and perceptual enhancements include frontal collision warning, side/rear/blind spot/lane change warning, lane departure warning, loss of traction (ice) warning, truck rollover warning, vision enhancement, driver performance monitoring/drowsiness warning, and intersection hazard warning.
- Driver control assists include autonomous intelligent cruise control, collision avoidance (braking and/or steering), lane holding (steering assistance), lane change/merge assist, vehicle shutdown based on driver or vehicle condition, and intersection hazard management.
- Fully automated systems include automated vehicles on special-purpose lanes, automated vehicles on their own freeway network, autonomous automated vehicles, and automatic parking.

The fully automated systems are already "systems" that integrate a variety of different functions. The driver warnings, perceptual enhancements, and control assists can be further integrated using a "driver's associate" or "copilot" to prioritize the information coming from the various sensors and individual subsystems. Then the driver would not be overwhelmed with multiple simultaneous stimuli or instructions.

POTENTIALLY SIGNIFICANT IMPROVEMENTS to road transportation operations could be gained through widespread deployment of Advanced Vehicle Control Systems. These improvements are likely to be most apparent in safety and system capacity. Many technologies need to be integrated carefully to make these systems a reality. The bulk of the required effort is not likely to be on the elemental technologies themselves but on their integration and adaptation to the specific application needs of AVCS.

Efforts in this field must remain strongly focused on finding solutions to transportation problems rather than on developing technology for the sake of technology, which can all too easily degenerate into "solutions looking for problems." Close coordination must be maintained between the basic research community, with its solutions (or possible solutions), and the transportation community, with its problems. Since the cultures of these communities are quite different from each other, substantial good will and effort are needed to bring them together into a mutually productive partnership.

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## References


1. K. Gardels, "Automatic Car Controls for Electronic Highways," General Motors Research Laboratories, Warren, Mich., Report GMR-276, 1960.
2. Y. Oshima et al., "Control System for Automatic Automobile Driving," *Proc. IFAC Tokyo Symp. Systems Engineering for Control System Design,* 1965, pp. 345-357.
3. K.H.F. Cardew, "The Automatic Steering of Vehicles—An Experimental System Fitted to a DS Citroen Car," Road Research Laboratory Report RRL LR 340, Crowthorne, England, 1970.
4. Ohio State University, "An Investigation of Highway Automation," Ohio State Univ. Reports EES 276A-6, 1969, and EES 276A-15, 1974; "Fundamental Studies in the Longitudinal Control of Automated Ground Vehicles," Report FHWA-RD-77-28, 1976.
5. J.E. Anderson et al., eds., *Personal Rapid Transit,* Institute of Technology, Univ. of Minnesota, 1972.
6. J.E. Anderson, ed., *Personal Rapid Transit II,* Institute of Technology, Univ. of Minnesota, 1974.
7. D.A. Gary, ed., *Personal Rapid Transit III,* Institute of Technology, Univ. of Minnesota, 1976.
8. "Advanced Transit and Urban Revitalization, An International Dialogue," *Proc. Int'l Conf. Advanced Transit,* Advanced Transit Association, Indianapolis, Ind., May 1978.
9. *Proc. TRB Conf. Dual Mode Transportation,* Transportation Research Board, Washington, D.C., Special Report 170, 1976.
10. *IEEE Trans. Vehicular Technology,* Vol. VT-19, No. 1, Feb. 1970.
11. *IEEE Trans. Vehicular Technology,* Vol. VT-28, No. 1, Feb. 1979.
12. *IEEE Trans. Vehicular Technology,* Vol 40, No. 1, Feb. 1991.
13. D.H.M. Reekie, E.R. Case, and J. Tsai, eds., *Proc. First Vehicle Navigation and Information Systems Conf.*, Toronto, Ontario, 1989.
14. "Advanced Telematics in Road Transport," *Proc. DRIVE Conf.*, Elsevier Publishers, Amsterdam, 1991.
15. *Proc. Vehicle Navigation and Information Systems Conf.*, P-253, Society of Automotive Engineers, Warrendale, Penn., Oct. 1991.
16. *Proc. Vehicle Navigation and Information Systems Conf.,* Society of Automotive Engieners, Sept. 1992.
17. *Proc. 24th ISATA Int'l Symp. Automotive Technology and Automation, Dedicated Conf. on RTI/IVHS,* Automotive Automation Ltd., Croydon, England, May, 1991.
18. "Surface Transportation and the Information Age," *Proc. Second IVHS America Annual Meeting,* May 1992, IVHS America, Washington, D.C., Report IVHS-AMER-92-4, Sept. 1992.
19. *Proc. American Control Conf.*, American Automatic Control Council, Institute of Electrical and Electronics Engineers, Piscataway, N.J., May 1990, pp. 268-303, 782-811.
20. *Proc. American Control Conf.,* IEEE, June 1991, pp. 2539-2572, 3078-3124.
21. *Proc. American Control Conf.*, IEEE, June 1992, pp. 1738-1778.


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# Intelligent Cruise Control and Roadside Information

**The on-board Autonomous Intelligent Cruise Control system controls a vehicle's speed according to the driver's desire and the speed of and distance to the preceding vehicle. Volvo developed, realized, and tested such a system, with enhancements. This system offers a one-directional short-range system for vehicle-vehicle and roadside-vehicle communication and considerations for recommended speed, limits, and traffic signals. It is potentially a key element in linking and integrating the driver-vehicle-infrastructure in future intelligent transportation systems.**

*Ulf Palmquist*

*AB Volvo*

An on-board vehicle system designed to control the longitudinal velocity at a driver's set value as well as the velocity of and the distance to a preceding vehicle offers several advantages. Compared to the traditional cruise control system found in many vehicles today, the Autonomous Intelligent Cruise Control, or AICC, system uses this information to adjust the vehicle's velocity to that of the preceding vehicle and keep it at a safe distance. Drivers will appreciate the comfort and safety offered by these extra functions. This system encourages smoother driving and, especially when the controllers are well tuned, reduces fuel consumption and the amount of harmful pollutants expelled into the environment, and better harmonizes traffic since acceleration and braking are also reduced.

Adding short-range vehicle-to-vehicle and roadside-to-vehicle communication to an AICC system lets drivers receive more accurate vehicle and traffic data at an earlier stage. (See Figure 1.) Drivers and their vehicle systems can access information about the status of surrounding traffic and take earlier, appropriate actions.

Systems of this sort are currently under intensive study and development in the Road and Traffic Informatics (RTI) programs in Europe, the United States, and Japan.[1,2]

## System description and requirements

Simply described, AICC requires, besides the ordinary vehicle sensors and systems, a target sensor to detect and measure the distances to preceding vehicles. Measurement of the relative velocity is an advantage but not a prerequisite. AICC must contain some intelligence and computing power for the evaluation and interpretation of sensor data, determination of appropriate control actions, and selection of information to the driver. The actual velocity control requires local control systems for accelerating and braking. A simple and sufficient man-machine-interaction unit exchanges commands and information with the driver, and a computer network or bus lets data flow between the hardware units. Since this is a real-time multievent application, real-time multitasking software should be used.

**Target sensor.** The zone in front of the AICC vehicle, of relevance for its velocity control, is not trivial to define. It depends on the demand one has of the system, the handling properties of the vehicle, the actual road conditions (for example, friction between road and tire, road curvature), and the velocity of the vehicle. Since AICC is designed primarily for country and highway driving (not heavy urban traffic), a target sensor should cover a zone of relevance defined as three



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lanes at a distance of zero to, say, 150 to 300 meters; see Figure 2. With a coverage of three lanes, the lane of the AICC vehicle and the lanes to the left and to the right can be scanned. Scanning the adjacent lanes is necessary as vehicles may be overtaking the AICC vehicle and moving into its lane. The range of 150 to 300 meters strongly depends on the conditions under which the AICC system should operate. The well-known formula

$$d = v \cdot T + v^2/2r$$

expresses the distance $d$ required to stop a vehicle at initial velocity $v$. The first term, $v \cdot T$, is the distance traveled during the reaction time (pure delay) of the driver and/or the system. The second term, $v^2/2r$, is the braking distance required when applying the retardation value $r$. As an example, consider the case $v$ = 120 km/h (33.3 meters/s), $T$ = 1.0 second, and $r$ = 2 meters/s$^2$ (maximum retardation for comfort). The braking distance for this case is 311 meters. Hence, if the AICC system must be able to stop in front of static obstacles from an initial velocity of 120 km/h, the target sensor needs to have a range of more than 300 meters.

From a systems point of view, it is natural to require a target sensor that covers a zone of relevance of 150 to 200 meters. The sensor should be able to detect objects from motorbikes to trucks and to measure the distance and the direction to them. As an advantage, the relative velocity can be measured independently, that is, not constructed as a function of distance measurements.

The sensor should be intelligent enough to filter out background noise and disturbances such as echoes from roadside railings and road signs. An ideal target sensor is one that delivers only the distance, the angle, and the relative velocity to objects like motorbikes, cars, and trucks in the zone of relevance. The sensor must function under clear weather conditions as well as in rain, fog, and snow. Today, scanned or multibeam radar and laser systems appear to be the most promising and reasonable choices to implement these needs.

**Signal processing and control unit.** The hardware unit is a computer that executes algorithms for signal evaluation, interpretation of traffic, decision and determination of control actions, and choice of information to the driver. The signal processing algorithms use the signals from the target sensor and from vehicle sensors as input (velocity, steering angle, yaw rate). Signal processing reduces the noise level of the signals and estimates the states of the AICC vehicle and all other vehicles detected in the zone of relevance. This means that, among others, the two-dimensional velocities of the vehicles and their relative positions have to be estimated.

The control algorithms use the estimated states produced by the signal processing and the driver's set speed as input. Based on these data, the control algorithm determines the correct restriction for the longitudinal velocity (driver's set speed or a preceding vehicle) and calculates the control actions to be implemented by the actuators. The physical form of the control actions depends on how the AICC system is decomposed. A natural decomposition leads to control actions of either velocity or acceleration (positive and negative) commands.

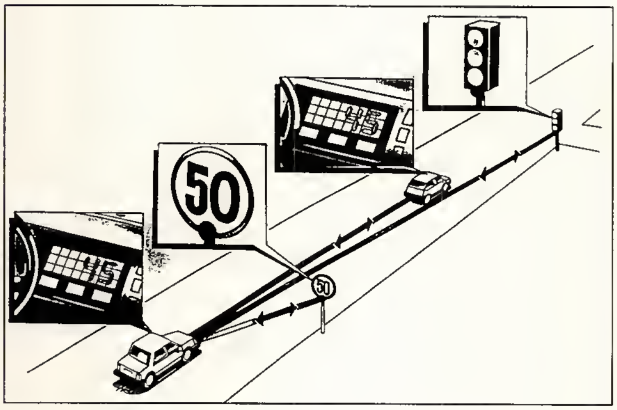



Figure 1. Intelligent cruise control system extended with communications for roadside information.

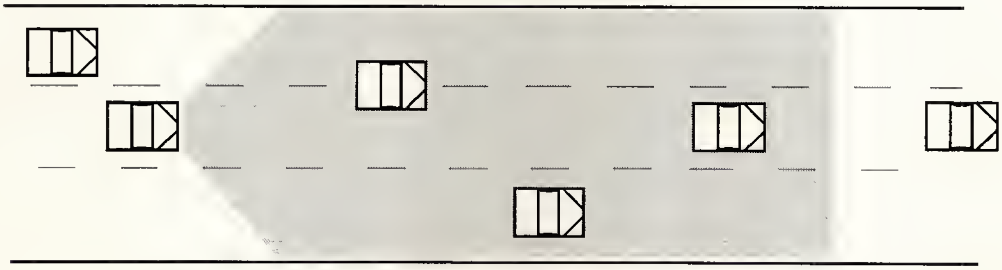


Figure 2. Zone of relevance.

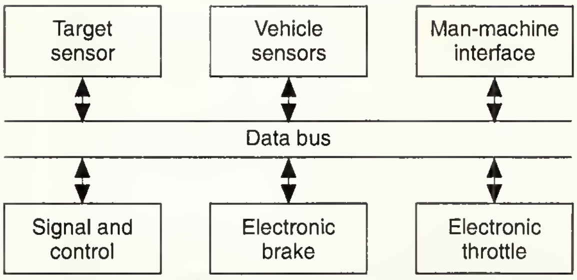



Figure 3. AICC subsystems and their interconnections.

**Actuators for velocity control.** The AICC system must have local control and actuator systems to adjust the vehicle's velocity in an efficient and smooth fashion. Inputs to these local systems are the control commands from the control unit (velocity, acceleration, and retardation commands).

Two systems are used to fulfill these requirements. An electronic throttle system can accelerate and keep the velocity constant. It can be thought of as a smart actuator that controls the actual acceleration or velocity close to the commanded one. The other is an electronic braking system in the form of a smart actuator that adjusts the actual retardation so it is sufficiently close to the commanded one.

**Man-machine-interaction.** This unit exchanges commands and information between the driver and the AICC system in a simple way at a sufficient level. The driver should be able to give the following commands and values to the AICC system:

- activate system,
- deactivate system,
- reactivate system,
- set speed value,
- increase set speed, and
- decrease set speed.

This input can, of course, be facilitated in many ways. Say the driver is not allowed to choose combinations of the functions of the AICC system (it is either turned off or turned on with all functions in operation). It seems most reasonable then to use the commonly accepted input pushbuttons of the traditional cruise control system for the AICC system also.

The driver must also be able to override the system manually at any time. Therefore, when wanting to go faster (pressing the accelerator pedal) or slower (pressing the brake pedal), the driver overrides the system. Note that the driver is fully responsible for the vehicle and its operation and, consequently, must have the overall control of it.

At any moment the status of the AICC system and its operation should be clear to the driver. Therefore, it must at least deliver the following information:

- verification of the driver's input,
- mode of operation (passive or active), and
- object for control (driver's set speed or preceding vehicle).

Today, no clear recommendations can be given on the content and form of this information to the driver. Displays and artificial voice are, of course, considered as candidates for output media.

**Network and software architecture.** The units in the AICC system have computing needs and capacities, and they continuously exchange information and commands. Implementing such a system requires an efficient network and software architecture. The philosophy of system design today is to distribute the tasks, with the corresponding computing capacity, and to connect these local units (or local nodes) with a common data bus. Variables and signals used only within a local unit are restricted to that unit, while variables and signals of relevance to more than one local unit are passed on to the common data bus and accessible to any connected unit. Figure 3 describes this structure.

Each unit must have an interface layer of hardware and software toward the bus to satisfy the specification of the common data bus. Furthermore, global variables and protocols for their transfer have to be defined. The implementation of application software, limited and local to a unit, should be possible with the only restriction that it does not disturb the transfer of the common variables at the data bus.

**Short-range communication.** By definition, the truly autonomous intelligent cruise control system uses only passively reflected waves from the target sensor in its detection and measurement of preceding vehicles. The advantage of this system is that it does not require equipment mounted on other vehicles for their cooperation. The drawback is that the data received is not always reliable; often the noise level is high, and echoes from objects along the roadside may disturb the measurements and target tracking.

Adding a system for short-range communications, SRC, between vehicles and between the roadside and a vehicle can improve the detection and measurement of preceding vehicles and also extend the functionality of the AICC system. It can transfer absolute or relative positions and vehicle state data from vehicle to vehicle as well as data from roadside equipment, for example, speed limits, status of traffic signals ahead, curvature of bends in the road. With this subsystem, the AICC system can more accurately adjust the vehicle's velocity. The SRC system can be incorporated as just another sensor of velocity restrictions within the AICC. With a structure of the hardware and software as just explained, it is quite easy to include the data from this sensor.

## Volvo's AICC system

The AICC system we developed and designed assists drivers in adapting their speeds with regard to

- the desired cruise speed,
- the distance to and the velocity of the preceding vehicle,
- speed recommendations and limits, and
- traffic signals and Green Wave systems. (A Green Wave system constitutes a number of coordinated traffic signals yielding green periods at the arrival of vehicles traveling in compliance with the recommended speed.)

Note that the Volvo AICC system has functions similar to those described in Figure 1.

Though the system structure largely follows that already described, it differs in one major way. Our AICC system is equipped with a transponder-based SRC system for acquisition of data from preceding vehicles and the roadside.

**Vehicle.** The vehicle equipped with our AICC system (pictured in Figure 4) is a standard 1991 Volvo 960 model with electronic control of the gear box.

**Target sensor.** The autonomous operation of the AICC system uses a target sensor made by Leica[3] and consisting of five fixed, nonoverlapping infrared beams. Each beam has a range of 150 meters and an angular coverage of 1.5 degrees, horizontally and vertically. Since the beams are not active simultaneously during measurement, it is possible—by knowing which beam caused a received echo and measuring the time of flight—to obtain the distance and angle (crude, in multiples of 1.5 degrees) to the reflecting object. The sensor cannot distinguish between objects separated less than 5 meters longitudinally, and it delivers the measurements corresponding to the closest object (it yields the first and often strongest echo). The sensor can detect objects the size of motorbikes, cars, and trucks. It also easily relays echoes from road signs and other objects along the roadside. Relative velocity is not available from this sensor.

**Short-range communication.** To transfer data from the preceding vehicle and the roadside, our AICC vehicle uses a transceiver/transponder-based SRC system. The Swedish Institute of Microelectronics developed this system, named Compose, within the Swedish RTI program.[4] (COM stands for communication and POS for position.)

In the AICC vehicle a transceiver unit, mounted in the front, transmits 17.5-GHz microwaves. Any transponders, in the rear of preceding vehicles and as beacons along the roadside, receiving the microwaves amplify the magnitude and modulate the frequency of the waves before reflecting them. The modulation allows the reflected wave to carry data. The transceiver unit measures the phase shift of the reflected wave and its delayed arrival between three patched antennas and determines the distance and angle to the transponder. Therefore, both measurements of the transponder position and data transfer are possible with the Compose system.

The transponder modulates the frequency according to either a programmed static data set in the transponder (static transponder) or data fed into the transponder continuously from an external device (dynamic transponder). The static transponders mainly supply static roadside information, while the dynamic transponders transmit time-variant data, for example, vehicle state data, status of traffic signals, and Green Wave periods.


Figure 4. Volvo's AICC demonstrator vehicle.

In our AICC system, the major task of the Compose system is to obtain speed recommendations and limits, traffic signal status, and other road sign information.

**Signal processing and control.** We developed and implemented model-based methods for the signal processing of sensor data and decisions and determinations of control actions in the signal processing and control unit of the AICC system.

As described earlier, the signal processing unit takes the target sensor data and—provided, of course, that the vehicle is equipped with a transponder—the data transmitted by the Compose system from the preceding vehicle as input. The signals from the sensors in the AICC vehicle (speed, steering angle) also become inputs. State estimators, constructed from dynamic models of the movement of the AICC vehicle and preceding vehicles, use these inputs to estimate the states of the AICC and preceding vehicles. These extended Kalman filter[5-6] state estimators combined with gating techniques[7] initiate, track, and delete model states of target vehicles.

The control unit has to take into account the following five restrictions or control objectives:

- driver's desired cruise speed,
- distance to and velocity of the preceding vehicle,
- actual speed limit,
- speed limit ahead, and
- traffic signal ahead.

The separate realization of each of these five restrictions is a control problem in itself; some are not at all trivial to fulfill.

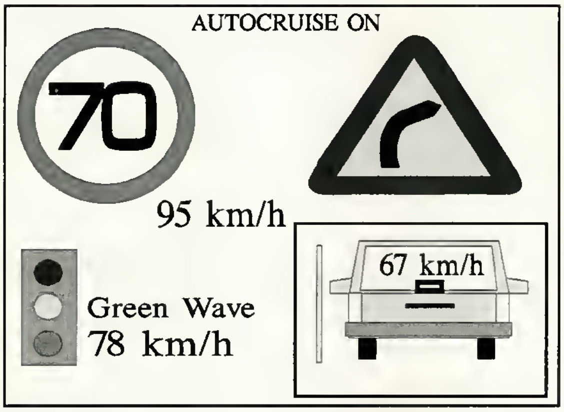



Figure 5. Displayed AICC information.

Furthermore, the combination and simultaneous execution of each requires a well-structured control unit. Note that the first four restrictions imply upper bounds on the velocity and acceleration of the AICC vehicle. The fifth restriction implies an upper and a lower bound on the velocity trajectory of the AICC vehicle so it can pass the traffic signal during a green period.

Since a velocity change of the AICC vehicle can be achieved by an acceleration command to the actuators, it is natural to design separate regulators—one for each of the five restrictions—whose outputs are acceleration commands. The outputs from the first four regulators will be the upper bounds on the permitted acceleration, while the fifth regulator will yield an interval for the acceleration.

Finding the minimal acceleration command among those from the five regulators lets us find the restriction that overrules the other four restrictions and determine which control command should be implemented. This procedure has several advantages. Each regulator can be separately designed to meet the corresponding restriction or criteria. Viewing the acceleration command instead of the actual velocity restriction implies better prediction of how the state will satisfy the restriction. Furthermore, this structure is flexible in the sense that other restrictions can be incorporated in the same fashion, for example, safe driving through a sharp bend with preinformation about the curvature and road/tire friction.

**Actuators for velocity control.** For the actual control of the longitudinal velocity, we installed two local control and actuator units in the AICC vehicle. These are a throttle system from Hella and a braking system from Bosch; both are electronically controlled.

The throttle system can be operated in three different modes, yielding a choice between the following desired control commands: speed, acceleration, and throttle angle.

The braking system is basically the Bosch ABS model with an electronically controlled plunger system above the ABS level. (The ABS function guarantees antilocking of the brakes. Since the AICC operates above the ABS level, the antilocking function is kept intact.) It can be operated in either of the two control command modes: desired retardation or desired brake pressure.

**Man-machine-interaction.** The MMI technique in our current AICC system has not been finally developed or adapted to the driver's need and ability. We used the pushbuttons in the traditional cruise control system for the input of the driver's commands and set values. These are

- activate system,
- deactivate system,
- reactivate system (resume),
- set speed value,
- increment set speed, and
- decrement set speed.

When the driver pushes the set button to activate the system, the set speed value is taken as the actual velocity of the vehicle simultaneously. The driver can override the AICC system at any time by pressing the gas pedal or the brake pedal.

Information from the system to the driver is shown as symbols (see Figure 5) on a color display mounted in the dashboard. Basically, the display shows information regarding the four restrictions of actual speed limit, driver's desired cruising speed, traffic signal ahead and its green period, and the distance to and the velocity of a preceding vehicle when they are potentially in force. The display indicates the symbol corresponding to the restriction the control unit has chosen by outlining it in black borders.

This information lets drivers see that the system has interpreted the situation correctly and that it takes the appropriate control actions. The displayed information also allows the system to operate in an informative mode. That is, the AICC system only delivers the information to the driver, who in turn must manually control the velocity of the car. The AICC system, in this mode, does not implement any control actions. We plan to use and examine this mode in the development phase. The upper-right quarter of the display shows road signs that do not necessarily contain information for AICC velocity control but are relevant to the driver for the safe operation of the vehicle. As an example, the upper-right corner of Figure 5 displays the road sign for a sharp bend.

We do not expect nor intend this MMI description to be the one used in a final AICC system; we designed and used it only for the purpose of development.

**Network and software architecture.** A common controller area network (CAN)[8] carries out the information exchange among the components and subsystems of our AICC system. The software is divided into three layers. The top application layer contains the application programs (signal

processing, controllers ), which are implemented in the form of C processes. The next layer provides real-time, multitasking services to the application programs. This layer uses a vehicle distributed executive (VDX), which is an operative software for the organization of distributed real-time processes and the network communication between them.[9] Finally, a network layer connects the VDX to the CAN network. Though use of the various layers has many purposes, one is worth mentioning: The application programmer should not have to bother with multitasking and network services.

## Linking to the infrastructure

The AICC is in itself truly an interesting and promising system. However, its value can be further enhanced by using the SRC link to pass information from the infrastructure to the AICC vehicle and its driver. A requirement is, of course, that the roads and streets are equipped with transponders yielding sufficient and necessary information.

The system requires two basic types of information: static and time variable (dynamic). The static information (speed limits, curvature of bends, warnings of school areas) can be preprogrammed into self-contained transponders that only require a power supply. The dynamic information (road conditions, recommended speeds, traffic signal status) is either directly generated by some smart sensors or provided by a local or regional traffic management center. Both have a data link to the appropriate transponders to distribute this information to passing vehicles.

As an example, consider the case of traffic flow control shown in Figure 6. Sensors along or in the street (for example, induction loops) detect and measure passing vehicles. The sensors feed data about the types of vehicles and their speeds to a local traffic manager whose task it is to obtain an efficient and harmonious flow of traffic. The manager continuously evaluates the received data to find the optimal time settings of the traffic signals as well as the suitable velocity to recommend to the vehicles. This manager also handles requests for intersection priority by special types of vehicles (public transport and heavy trucks).

For a harmonized flow of traffic, control of more than just the traffic signals is necessary; preinformation must be given to the vehicles and drivers approaching the intersection so that they can adapt to the active restrictions in due time. The local traffic manager uses the roadside transponders to distribute adequate data to the passing vehicles. This data should contain information about the distance from the transponder to the intersection, the time until the start and end of the next green period, the cycle time of green period, and the length of queuing vehicles. Then the driver can adjust the vehicle's speed to pass the intersection during the green period. Furthermore, for a smooth flow of traffic the transponders should also give preinformation about the status of the traffic signals at the next two or three intersections ahead.

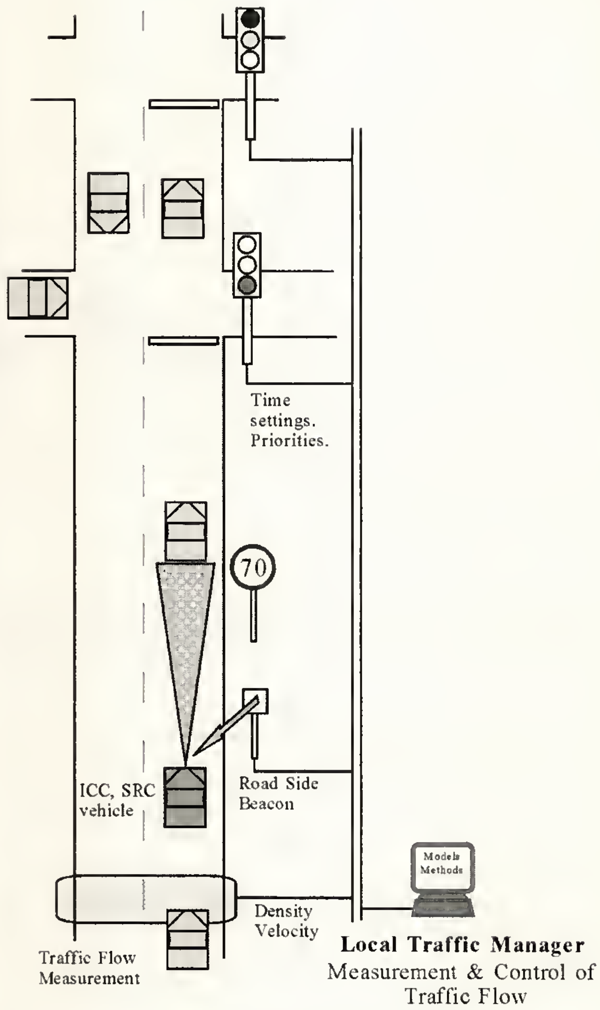



Figure 6. Traffic flow control using intelligent cruise control and SRC.

An AICC vehicle picking up this transponder information determines a velocity profile that also takes into account minimal fuel consumption and pollutant emissions. The display of the complete velocity profile in the form of the recommended velocity lets drivers accept and fulfill a command (informative mode) or choose to feed the data into the AICC system for automatic realization (automatic mode).

Preceding vehicles also have to be considered and evaluated in combination with the traffic signals ahead. The system accomplishes this by continuous evaluation of the information gained by the distance sensor mounted in the front of the AICC vehicle. Consequently, when approaching a vehicle ahead, it changes the priority of the control objec-

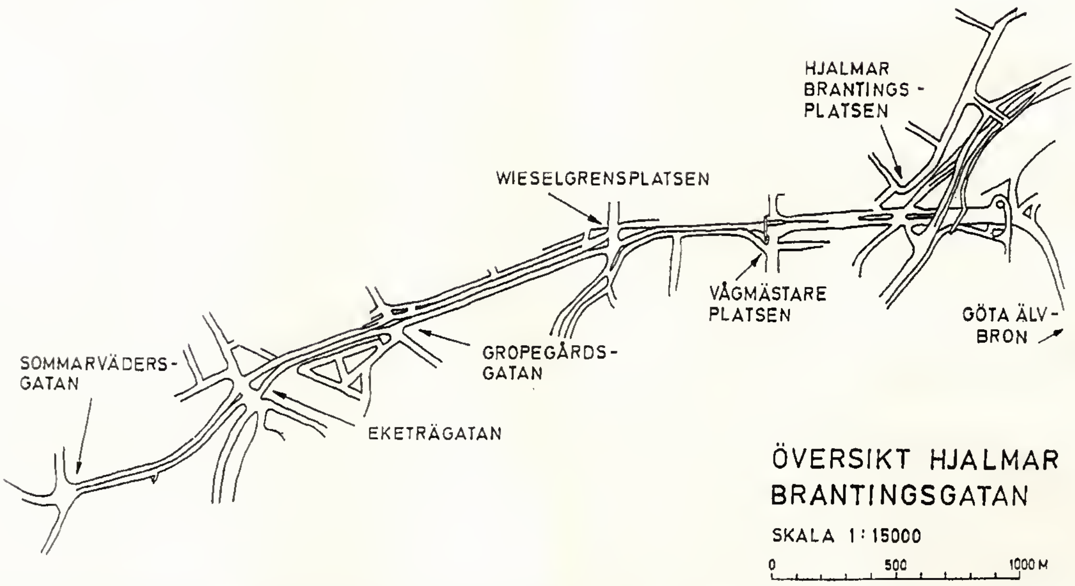



Figure 7. Field trial for traffic flow harmonization at Hjalmar Branting Street.

tive from that of passing at a green period to having a safe distance to the vehicle ahead.

This system can be viewed as a multifeedback control system, in which

- control of the traffic flow is a global loop,
- adjustment of the driver and the AICC vehicle to the traffic signals is an inner loop, and
- adjustment of the driver and the AICC vehicle to the preceding vehicles is a local loop.

These loops constitute the linking of the driver-vehicle-infrastructure.

Note that the idea of giving recommended speed information to the driver is not new. Experiments using radio links to the vehicle have been executed in Wolfsburg, Germany,[10] and Melbourne, Australia.[11] In these experiments the driver was informed of the recommended speed on a display and manually adapted the car's velocity. Reduction in fuel consumption and emission of pollutants, without loss of travel time, were proved.

The Melbourne trials as well as evaluation of systems giving recommended speeds on variable signs along the road[12] show, however, that drivers did not adapt particularly well to the given recommendation. When the recommended speed was low, drivers drove too fast and arrived too early for the green period; when it was high, the drivers drove too slowly. Also when the recommended speed was given only at discrete locations along the road, drivers were not well suited to adapt speeds for any longer distances. Thus, allowing the AICC system to assist drivers and automatically adjust the velocity seems to be a promising step toward harmonized traffic flow.

## Field trials

The described RTI technology and systems are not just visions for the future. As a part of the area Driver Assistance and Local Traffic Management within the Swedish RTI program 1991-94, Volvo, Saab, and the Swedish National Road Administration collaborate. They are executing two field trials to explore the technology and feasibility of these systems. These field trials are located in the Arena Test Site West Sweden, which is an open real-traffic RTI laboratory. Located on the west coast of Sweden, the site covers the greater Gothenburg area.

**Traffic flow harmonization.** Harmonizing the flow of traffic has a potentially positive impact on the protection of the environment and the reduction of fuel consumption. The objectives of the harmonization field trial are to explore and estimate the effects on traffic efficiency, fuel consumption, and pollutant emissions when providing AICC vehicles and drivers with preinformation about speed limits (present and future) and the status of traffic signals ahead.

Hjalmar Branting Street is a highway located in the city of Gothenburg. A 3.5-km stretch of the street has speed limits of 50 km/h and 70 km/h, and six signal-controlled intersections, as shown in Figure 7. The timing of the traffic signals are static but fixed to yield a green period when traveling at

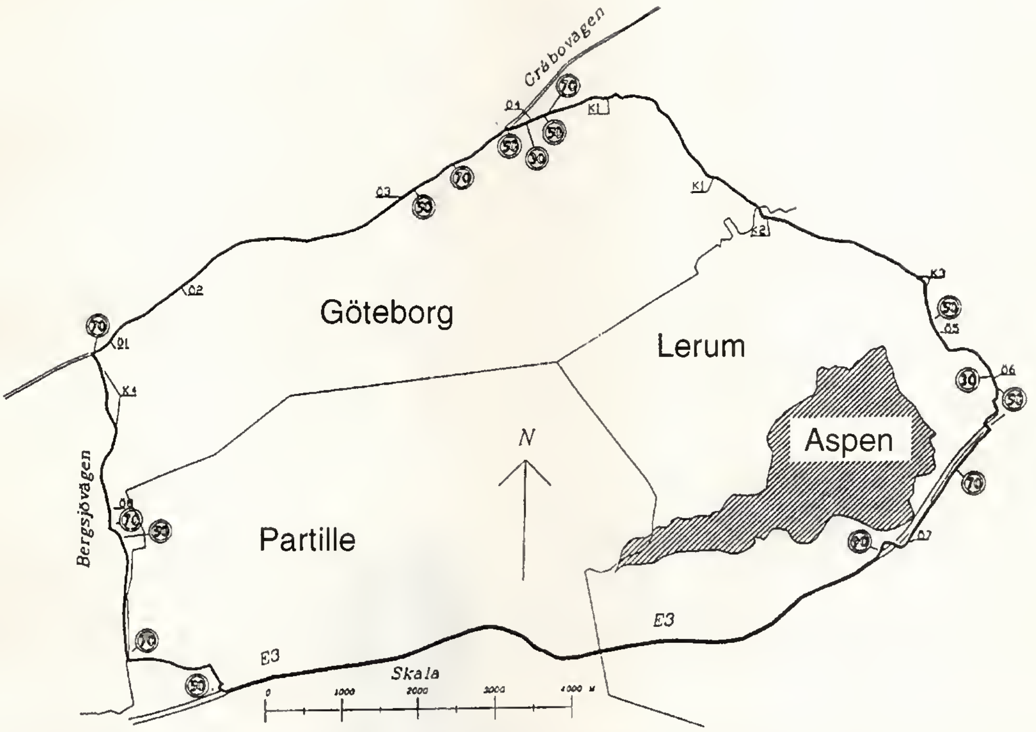



Figure 8. Aspen Track roadside information for active safety.

the appropriate speed. (This speed is not announced and is generally unknown to ordinary drivers.) This street has been equipped with a number of Compose transponders. Each transponder gives information on the speed limit and the status of the traffic signals at the next three intersections, more or less in accordance with that previously described.

AICC SRC-equipped vehicles from Volvo and Saab will be driven in a series of designed runs by ordinary drivers on Hjalmar Branting Street. The following three different driving modes will be investigated:

- *Manual.* With no RTI support, the driver has to manually adjust the speed of the vehicle.
- *Informative.* With information about the speed limit and green period recommended speed, the driver has to manually adjust the speed of the vehicle.
- *Automatic.* With the same information given to the driver as in the informative mode, the AICC system automatically adjusts the speed of the vehicle.

During the test runs variables such as velocity, fuel, and consumption are logged for later analysis of the effects of efficiency, fuel, and pollutant reduction. Based on those results, extrapolations to traffic in larger populations of AICC, SRC-equipped vehicles can be carried out.

Already, this field trial has provided technical experience concerning the SRC link and its advantages and drawbacks in a complex real-traffic environment. One very obvious result in particular is that a real traffic environment demands very robust and reliable SRC systems. More results from the field trial are expected to be available during 1993.

**Aspen Track, roadside information for active safety.** An SRC link from the roadside to passing vehicles yields the advantage of feeding information into the vehicle system so it can be given to the driver at the correct location and time. This information may change the driver's behavior and, as a consequence, have an impact on the safety not just of the driver but also that of the surrounding traffic and unprotected pedestrians.

East of Gothenburg around Aspen Lake is a track of approximately 35 km of rural and motorway roads, as depicted in Figure 8. Aspen Track has been equipped with transponders transmitting information on speed limits, road curvature, and recommended speeds on sharp bends, warnings of pedestrian crossings, and other relevant information. The field trial explores the effects on driver behavior and safety when using roadside information. The driving behavior of a number of ordinary test drivers using AICC SRC-equipped ve-

hicles from Volvo and Saab when driving on Aspen Track will be studied and logged. The modes of driving are similar to the one used in the traffic flow harmonization experiments.

- *Manual.* With no RTI support, the ordinary driver has to adjust the speed of the vehicle.
- *Informative.* With information about the speed limits, warnings, and so on, the driver has to manually adjust the speed of the vehicle.
- *Assisting.* With the same information, the AICC system automatically realizes the recommended speed.

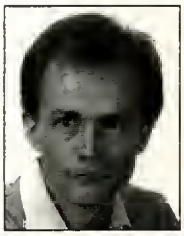
We executed this field trial at the end of 1992 and expect results from the evaluation in early 1993.

## Acknowledgments

The work I've described formed a part of the area Driver Assistance and Local Traffic Management within the Swedish RTI 1991-94 program. Parts of this work are Volvo's contribution to the AICC project within the European Eureka program Prometheus. The members of the Volvo AICC project team are all highly appreciated for their contribution to the development of the AICC system.

## References

1. D. Augello et al., "Traffic Flow Harmonization by Cooperative Driving," *ATA Proc. Third Int'l Conf.*, Vol. 3, Apr. 1992, pp. 1889-1898.
2. R.E. Fenton and R.J. Mayhan, "Automated Highway Studies at the Ohio State University—An Overview," *IEEE Trans. Vehicular Technology*, Vol. 40, No. 1, Feb. 1991, pp. 100-113.
3. Leica, "MSAR—Multi Segment Distance Sensor," Tech. Specification Z. 135/88 Rev. B, Leica Heerbrugg Ltd., CH-9435 Heerbrugg, Switzerland, Sept. 1989.
4. P. Henricsson et al., "COMPOSE—A Transceiver/Transponder System for Communication and Relative Positioning," *Proc. Prometheus Workshop*, Prometheus Office, Damiler-Benz AG, Postfach 60 02 02, D-7000 Stuttgart 60, Germany, Oct. 1989, pp. 327-337.
5. R.E. Kalman, "A New Approach to Linear Filtering and Prediction Problems," *J. Basic Engineering*, Vol. 82, Ser. D, No. 1, 1960, pp. 35-45.
6. A.H. Jazwinski, *Stochastic Processes and Filtering Theory*, Academic Press, New York, 1970.
7. S. Blackman, "Multiple-Target Tracking with Radar Applications," Artech House, Inc., Norwood, Mass., 1986.
8. D.J. Arnett, "A High Performance Solution for In-Vehicle Networking—Controller Area Network (CAN)," Society of Automotive Engineers, Tech. Paper 870823, Apr. 1987.
9. C. Serrano and M.A. Kung, "VDX: Vehicle Distributed eXecutive," Report 80-NT-442694, Renault, D. R., Paris, France, Dec. 1988.
10. G. Hoffman and W. Zimdahl, "Recommended Speed Indication Within the Motor Vehicle—A Contribution to Fuel Saving Through the 'Wolfsburg Wave' Information System," *Proc. Sym. Energy Efficiency in Land Transport*, Commission of the European Communities, Publ. EUR 12284 EN, Luxembourg, May 1988, pp. 211-222.
11. R.S. Trayford, "Testing Dynamic Advisory Speeds Under Adaptive Signal Control," *Australian Road Research*, Vol. 17, No. 4, Dec. 1987, pp. 243-255.
12. U. Hammarstrom, "Hastighetssignaler—effekt av efterlevnad," [Speed Recommendations—Effect of Compliance], Report 270, Swedish Road & Traffic Research Institute, Linkoping Sweden, (in Swedish), 1981.



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Chapter 5, the heart of the text, presents by example techniques for rendering visible information hidden in data. The chapter discusses what information is revealed by use of a specific technique and demonstrates the application of the technique in the accompanying image. References to additional literature are also provided. Although the 150 images are from a broad range of disciplines, the discussion of the techniques is presented independent of discipline to show readers that many visualization techniques can be generally applied.

To help the scientist and engineer relate particular visualization needs to the examples in *Visual Cues*, the authors display certain information for each example:

* A running head identifies images according to general ways of thinking about data.
* A 3-line index gives the number of variables in the image, describes the information revealed, and names the application.
* A succinct image caption indicates the techniques and the information revealed by the technique.

The text accompanying each image describes the application more fully, names the variables, and lists the hardware and software used to produce the image. An additional paragraph discusses the techniques that reveal the information. Other images containing related information are cross-referenced, and each example is evaluated with respect to the actual amount of computer power needed to accomplish the visualization.

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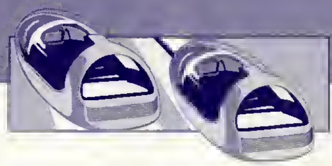

# Improving the Reliability and Safety of Automotive Electronics

**Microelectronics systems designed for automotive applications face an extremely hostile electrical and physical environment. Designers must produce increased component and system reliability while maintaining required compactness and cost-effectiveness levels. Their designs become crucial to all as we devote more electronic systems to safety-critical applications. We summarize the results of the European Prometheus PRO-CHIP research groups working on the reliability and fail-safe operation of microelectronic systems and devices.**

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*Paolo Pavan*

*University of Padua*

Reliability is a key issue for automotive applications of microelectronic systems. Future cars will be characterized by the increased use of integrated electronic systems (up to 25 percent of the total car manufacturing costs in the year 2000). The functions of these systems will vitally affect car safety and performance. According to a forecast from the European Prometheus project, the automobile of 1995 will have about 100 sensors, 80 actuators, 45 motors, 5 displays, 4 imagers, and 1,000 integrated circuits.[1,2]

The reliability goal forecast by the American automotive industry for the year 2000 is 0.01 ppm cumulative at five years or 50,000 miles, equivalent to 1,800 ignition-on hours. Unfortunately, the current reliability level of electronic components is not yet compatible with the ever-increasing complexity of the electronic systems required for automotive applications in the near future. We need to develop new methodologies for evaluating and improving electronic component and system reliability through research conducted with the close cooperation of system and device manufacturers.

The task is particularly difficult owing to the peculiarities of automotive applications. On one hand the automotive environment is one of the harshest, possibly accelerating a series of different failure mechanisms. On the other hand the required improvement in reliability must be obtained while respecting the specifications of low-cost, high-volume production, light weight, compactness, and short time-to-market imposed by the automotive industry.

We present some of the results and activities of the Prometheus project's PRO-CHIP research groups who studied these problems. We also briefly review the reliability problems most frequently encountered by electronic devices for automotive applications and the procedures the manufacturers use to evaluate and improve reliability of their products.

## The automotive environment

Past research of the automotive environment has made its characteristics fairly well known.[2,3] Temperatures within the engine compartment vary from approximately −40 degrees Celsius to +150°C, but the exhaust temperature can be as high as 650°C. Even below the dashboard or within the car interior, the temperature can reach 85°C. Thermal gradients can be extremely high, and a large number of thermal cycles (as high as 40°C/min) is expected during a device's operating life. Thermal cycles promote thermal fatigue phenomena and other failure mechanisms related to the mismatch of the thermal coefficients of the



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## Reliability tests for automotive electronic components

The following describes the accelerated testing usually adopted by the automotive industry to evaluate the reliability of electronic components and to qualify new suppliers.

**Air-to-air thermal shock.** Minimum dwelling time of 18 minutes at each extreme temperature. Common test temperatures are –40°C to 150°C and –40°C to 125°C. Test duration is 1,000 cycles.

**Air-to-air thermal cycles.** Minimum dwelling time of 15 minutes at each extreme temperature. Minimum ramp rate is 5°C/minute; common test temperatures are –40°C to 150°C and –40°C to 125°C. Test duration is 1,000 cycles.

**Liquid-to-liquid thermal shock.** Minimum dwelling ingtime of 3 minutes at each extreme temperature. Common test temperatures are –40°C to 125°C. Test duration is 500 cycles.

**High humidity/high temperature (optional bias).** Components to 85°C and 85 percent relative humidity. Test duration is 1,008 hours.

**Life test.** Components to their maximum operating temperature and power. Test duration is 1,008 hours.

**Hot storage.** Components to their maximum operating temperature. Test duration is 1,008 hours.

**High-temperature (reverse bias.)** Reverse-biased at the device's maximum temperature for 1,008 hours.

**Mechanical shock.** Three shocks in perpendicular planes. The devices will be shocked at 1,500, 3,000, 4,500, and 6,000 g levels. The minimum acceptable shock requirement will be 3,000 g/0.3 ms.

**Vibration.** From 5 Hz to 200 Hz for 10 ± 2 minutes per cycle. Repeat the cycle for five hours in each of three planes.

**Surge voltage test for capacitors.** Voltage surges at 130 percent of rated voltage, cyclically applied 30 seconds on and 30 seconds or 270 seconds off for $T_a$ and electrolytic capacitors. Typical test duration is 1,000 surges.

**Intermittent operational life.** A 75°C temperature variation for each cycle. Power rated at 85 percent applied for 1 minute and 1 minute cooling for each cycle. Test performed at 0°C or –10°C. Test duration is 20,000 cycles.

**Ripple life test.** Maximum operating temperature. Bias with 90 percent of rated ripple current and DC bias voltage. Test duration is 1,008 hours.

**Autoclave.** Requires 121°C, 2 atm, and saturated humidity. Test duration is 96 hours.

employed materials. Relative humidities up to 99 percent, together with the presence of corrosive chemicals (NaCl, CaCl, $SO_2$, ...) and fuel vapor can accelerate corrosion mechanisms. Instantaneous acceleration and shocks can be as high as 30g.[2]

Severe hazards can be produced from a variety of electromagnetic interference (EMI) and power supply transients, and high-voltage (≈100V, 100 μs to 2 ms) transients result from the presence of large inductive components. Electronic components in the car can be subjected to "load-dump" slow transients. These transients consist of a 10V to 120V positive overvoltage that is superimposed on the nominal 12V supply if a large load or flat battery is disconnected from the electrical system of a vehicle while the engine is running at high speed. This transient can last between 40 ns and 400 ms; it is the most severe electrical overstress that can be induced within the car electrical system.

Finally, susceptibility to EMI can be a critical issue due to the presence of intense sources of electromagnetic radiation also within the car itself. In the 5-kHz to 18-GHz frequency range, automotive electronics must withstand field intensities up to 100 V/m without errors.

Reliability testing of electronic components for automotive electronics must assure, in principle, that selected components will meet the failure rate goals specified by system designers. To identify the specific failure mechanisms of electronic components and the related acceleration factors, manufacturers have extensively used accelerated testing. Failure rates in nominal operating conditions have been successfully estimated on the basis of accelerated life test data. (See the box above.)

This traditional approach of "measuring" component reliability by means of accelerated tests and of extrapolating the results to field conditions will become less effective as the failure rates of electronic components continue to decrease. In fact, when the failure rate of the device to be tested is estimated in the 10-FIT (10 failures over $10^9$ component-hours) range, the task of evaluating its reliability is cost-prohibitive, both in terms of number of units and in terms of time.

As a consequence, new ways of evaluating the reliability of electronic devices have been proposed. The "wafer-level reliability" approach consists of highly accelerated wafer-level tests on discrete structures that are designed to address each specific reliability failure mechanism, such as time-dependent breakdown, electromigration, hot-electron effects. However, this method does not cover all failure mechanisms, and even in this case quantitative evaluation of very low failure rates becomes uneconomical.

A detailed in-line control of process variations and of input process variables that may affect device reliability will more effectively "build reliability" into devices. This approach requires the manufacturer of automotive electronic products to

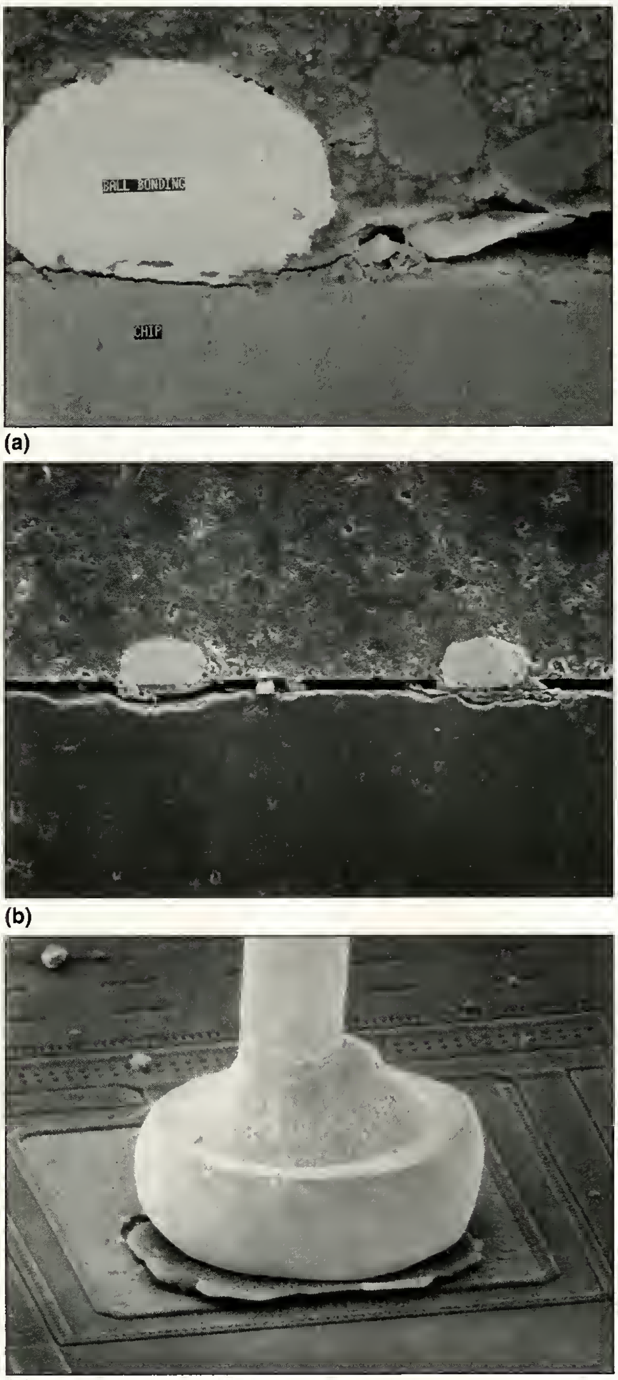


Figure 1. Cross section of a plastic packaged device, showing beginning of delamination of the plastic/chip interface (a,b) and breaking of bonding due to thermomechanical stress (c).

cooperate closely with the IC supplier, possibly developing common programs of reliability assessment and improvement from the very early stage of product design and definition. This does not imply that reliability engineering will reduce itself to a sophisticated kind of process monitoring. On the contrary, a large research effort must be undertaken to better understand device failure mechanisms, to identify which process variables can actually affect the long-term behavior of devices, to develop failure analysis techniques suitable for ULSI (ultralarge scale integration) circuits, and to define design guidelines for reducing the impact of electromigration, "latch-up," electrostatic discharge (ESD), and other failure mechanisms dependent on device scaling. For this reason most of the PRO-CHIP research groups developing new devices or technologies are also involved in reliability characterization, as summarized in Table 1.

## Building in reliability

The most frequently observed reliability problems of automotive electronic components generally relate to

1) failure mechanisms due to the package or to the assembling technology;
2) different kinds of electrical overstress, electrostatic discharge, electromagnetic interference; (All these can trigger parasitic bipolar elements of CMOS ICs, that is, latch-up.)
3) breakdown and burnout of power devices; and
4) failure mechanisms accelerated by high temperatures and high current densities.

**Failure mechanisms due to thermomechanical stress and thermal fatigue.** The trend toward integration of complete systems on a chip requires the placement of larger and larger chips into complex plastic packages with smaller outlines. Unfortunately, the repeated thermal cycling typical of automotive applications can lead to mechanical stress, induced by thermal expansion mismatches between the package materials (plastic compound, silicon chip, lead frame metal). In turn, this induces a series of different failure phenomena. The chip surface and die attach may be subjected to shearing stress, which results in damage to the metallization tracks and passivation cracks; the silicon itself can also be damaged. Say that delamination of the plastic/chip interface occurs, due, for instance, to humidity or contaminants (see the IC cross sections in Figure 1a,b). Then, the plastic can be displaced along the chip surface, resulting in deformations of metallizations and wire bonding and eventually resulting in the breaking of the bonding itself, as shown in Figure 1c.

The formation of a void between the plastic and the chip promotes the penetration of contaminants, inducing the cor-

*continued on page 34*

**Table 1. Reliability research groups within Prometheus PRO-CHIP.**

| Research title | Institution | In cooperation | Devices studied | Problem or failure mechanism (f.m.) | Failure analysis techniques/ design and test tools |
|---|---|---|---|---|---|
| Robust analog design | Institute for Microelectronics Stuttgart (D) | Siemens AG | Current and voltage reference circuits in CMOS; I/O protection circuits | Electrostatic discharge (ESD), EMI | — |
| Thermal design in power hybrid and high-density assemblies | LAAS CNRS Toulouse (F) | — | Hybrid MOS transistor power switches | Thermal behavior, DC/time dependent | |
| Reliability of components and assemblies in severe automotive environments | IXL, Univ. of Bordeaux (F) | Siemens Automotive, PSA, Thomson CSF | Tantalum capacitors, ceramic capacitors, packages for SMI | Fail. due to thermal cycles, mechanical shocks, humidity | Impedance f. analy., Piezoel. resonance, acoustic microscopy |
| Reliability of electronic components for automotive applications | Dip. di Elettronica e Informatica, Univ. Padova (I) | SGS-Thomson Alcatel-Telettra SpA | CMOS ICs, high-, medium-voltage MOS, GaAs devices | ESD, EMI, latch-up, hot-electron effects, f.m. of GaAs devices | Electron microscopy and microanalysis (SIMS, Auger) |
| Failure mechanisms, functional testing and electron-beam testing | Tecnopolis CSATA, Bari (I) | SGS-Thomson Alcatel-Telettra Siemens Telecom Marelli Autronica | CMOS ICs, high-, medium-voltage MOS, GaAs devices | ESD, EMI, latch-up, hot-electron effects, thermally activated f.m. of GaAs devices | Laser and electron microscopy, emission microscopy |
| Susceptibility of ICs to electromagnetic interference (EMI) | Dip. di Elettronica, Politecnico di Torino (I) | Centro Richerche Fiat | TTL and CMOS integrated circuits | EMI | — |
| Functional analysis of intelligent power circuits | LAAS CNRS, Toulouse (F) | PSA, Renault, Motorola Semicon. SGS-Thomson | CMOS, DMOS technology; MOS high-power switch | Latch-up, failure mechanisms of high-power MOS | — |
| Diagnostic functions for automotive smart-power switches | Robert Bosch GmbH Reutlingen (D) | — | Voltage-protected, smart ignition bipolar driver | — | — |
| Low-to-high power interfaces | Institute for Microelectronics Stuttgart (D) | Robert Bosch GmbH | Overcurrent, open-load, I/O prot. circuit in CMOS, power MOS | — | — |
| Smart-power devices in bond and etchback silicon-on-insulator (SOI) technology | Institute for Microelectronics Stuttgart (D) | Daimler Benz AG Forschungszentrum | 100V LDMOS, 150V VDMOS on SOI | — | — |

D: Germany, F: France, I: Italy

Figure 2. Corrosion of the pad bonding in a plastic device (top), resulting in an open circuit (bottom).

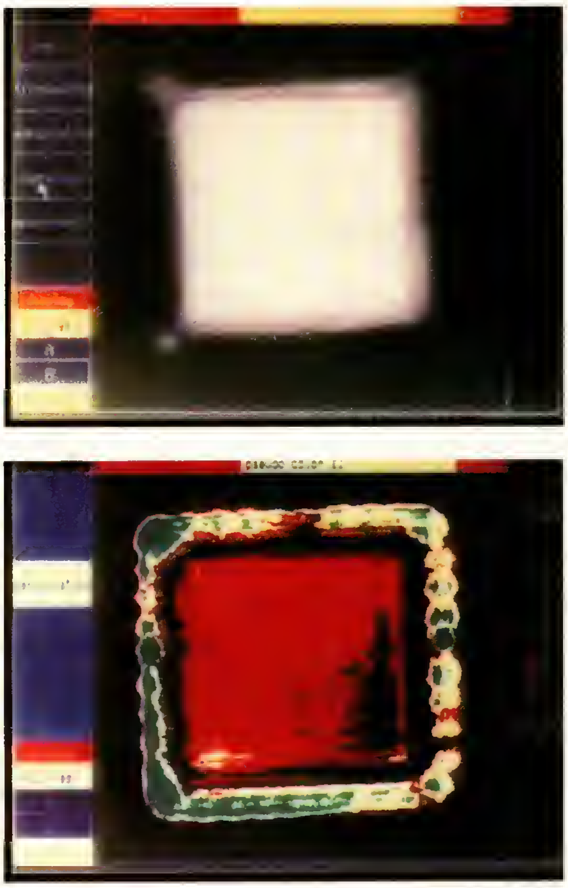

Figure 3. Acoustic microscopy map of a device without defects (top) and of a device in which a void has been created between the plastic package and the chip (bottom).

rosion of the metal pad and eventually resulting in an open circuit, see Figure 2. Defects in plastic encapsulated ICs can be observed nondestructively (without opening the package) by means of acoustic microscopy.[4] Separations of the molding compound from the lead frame or the die are nontransmissive and highly reflective to high-frequency ultrasound. Therefore they appear as high-contrast features in the image. Figure 3 compares the acoustic microscopy map without defects with that of a device in which a void has been created between the plastic package and the chip. The void corresponds to the dark area in the false colors image.

By measuring the linear thermal coefficient of the plastic compounds used for IC packaging as a function of temperature, we can obtain information on possible risks deriving from thermomechanical stresses. At a certain temperature, identified as the glass-transition temperature of the compound, $T_g$, a remarkable increase in the expansion coefficient occurs. Higher $T_g$ values correspond therefore to increased reliability levels. Figure 4 shows the linear thermal expansion of a package having a $T_g$ = 133°C. This is too close to the operating range of the device and results in bonding deformation after thermal cycling, as shown in Figure 5.

The trend toward increased miniaturization has also resulted in the diffusion of surface-mount technology, and in the need for new substrates that provide a better power dissipation for the components. A PRO-CHIP group directed by Danto at the University of Bordeaux IXL (France) has developed a tool to optimize the thermomechanical behavior of large plastic packages used for surface-mount assemblies.[5] The tool is based on two-dimensional simulation using finite element analysis. The simulations provide information concerning the location and strength of thermomechanical stresses as a function of physical parameters of adopted components.

The authors have submitted different kinds of assemblies,

including plastic quad flat packages (PQFP) and plastic leaded chip carriers (PLCC), mounted on alumina or on isolated metal substrates, to accelerated tests. The tests include −40°C to 150°C thermal cycles, 12 to 60 minutes flat time, and 85°C, 85 percent relative humidity factors. PLCCs on alumina show more failures than PLCCs on metal substrates. The latter provide the best results together with PQFPs on metal. Failures consist of cracks located at the solder-lead interface; these cracks coincide with points of maximum stress as identified by simulations, thus validating the chosen approach.

Another dangerous failure mechanism relates to the thermal fatigue phenomena of power devices, which result from the thermal mismatch between the chip and the header under stresses imposed by temperature or power cycling. The failure mode, for devices using soft solder, usually consists of voids and cracks in the solder material. These defects increase the device's thermal resistance, form "hot spots" in the chip, and eventually induce device burnout owing to thermal instability.

**Thermal characterization methods.** The channel temperature ($T_{ch}$) of an electronic device is conventionally described as the sum of the case temperature ($T_{case}$) and of the product of the power dissipation ($P_d$) by the thermal resistance ($R_{th}$). That is, $T_{ch} = T_{case} + P_d R_{th}$. We can evaluate $R_{th}$ and $T_{ch}$ by means of both DC and pulsed electrical methods. These methods are based on the measurement of a device's electrical characteristic (like $V_{BE}$ in a bipolar transistor), which is assumed to depend on temperature according to a known or measured calibration curve.

Electrical methods provide an average measurement of the temperature of the device. Unfortunately, in actual operating conditions, or during accelerated tests, the power dissipated by the device's active areas leads to a nonuniform increase of the device temperature. The $T_{ch}$ value resulting from electrical measurements is therefore an average, weighted in an unknown manner, of the temperature distribution on the device and can therefore be very inaccurate, especially if a small area of high temperature exists within the structure.

The actual temperature distribution on the chip can be measured by liquid crystal techniques or directly observed by means of high lateral resolution infrared (IR) thermography. We can then detect the thermal gradients caused by local differences in the heat dissipation or by structural inhomogeneities. This technique can perform surface temperature measurements of devices with a spatial resolution of 15 µm and a field of view of 1.8 × 1.8 mm$^2$. Figure 6 (p. 36) shows the IR thermography map of a 0.25W gallium arsenide (GaAs) MESFET device, biased at $P_d$ = 640 mW, at $T_{case}$ = 24.8°C.

Thermal design of the automotive electronic power circuits markedly influences their reliability; consequently, it is of great importance to develop suitable tools for the thermal design of these circuits. This has been the goal of the project conducted by J.M. Dorkel and collaborators at LAAS CNRS Toulouse, which developed the Pyrtherm package based on the use of the Thermal Influence Coefficient.[6,7] This package enables 3D static simulation of complex assembly structures to be easily performed on a personal computer in the interactive mode. It optimizes the thermal structure, hybrid assembly, or component location to obtain a minimal thermal resistance or thermal increase. The group compared the results with temperature maps produced with IR thermography. A 3D thermal step response can be computed for an elementary disk-shaped power source located on top of a rather complicated cooling structure. Using the superposition principle and evaluating a convolution integral, we can compute the thermal response for any power dissipation pulse.

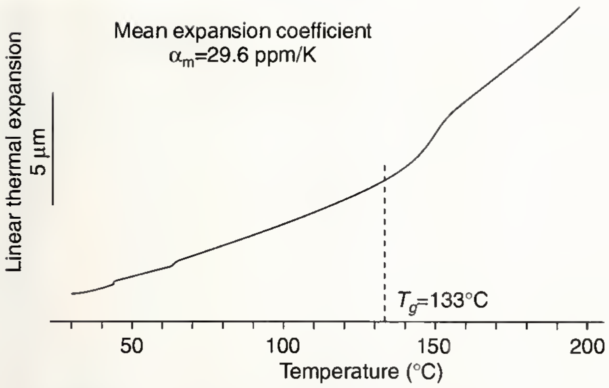


Figure 4. Linear thermal expansion of a plastic package as a function of temperature, identifying a glass transition temperature $T_g$ = 133°C.

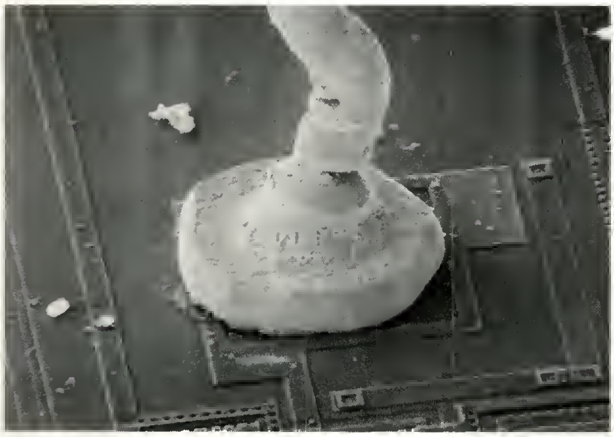

Figure 5. Wire-bonding deformation due to thermomechanical stress in the same IC as in the previous figure.

**Managing electrical overstress, electrostatic discharge, electromagnetic interference.** Because of the intense elec-

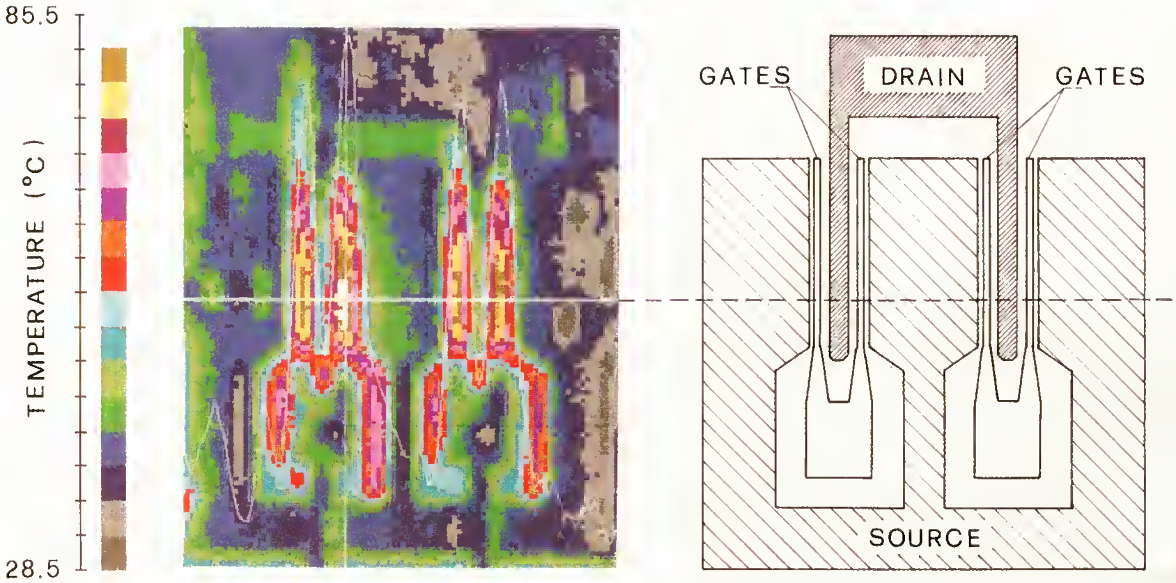


Figure 6. Infrared thermography map of a 0.25W MESFET, biased at $P_d$ = 640 mW, $T_{case}$ = 24.8°C.

trical noise present within a car, failure mechanisms from I/O overcurrent and overvoltages are a serious concern in automotive electronic systems. The techniques for protecting ICs from electrical overstress include both special layout and technology of I/O devices and networks, and specific integrated protection circuits. These circuits enable the device to protect itself against electrical overstress before a permanent failure can occur. More subtle failures can be induced by the triggering of parasitic elements and by electrostatic discharge.

**Latch-up in CMOS ICs.** Scaling CMOS ICs can include reliability hazards due to the action of the parasitic semiconductor-controlled rectifier (SCR) unavoidably present in bulk CMOS technology. If switched on, this parasitic SCR can connect supply voltage $V_{DD}$ and ground voltage $V_{SS}$ by a low resistance path. This phenomenon is called latch-up and can be induced by overvoltages applied to I/O or supply lines. When latch-up is triggered, the circuit no longer meets its functional specifications, and a large current flows through the parasitic structure, permanently damaging the device.

Figure 7a shows the simplified cross section of a double-well CMOS device. The parasitic PNPN structure consists of NPN ($Q_n$) and PNP ($Q_p$) bipolar transistors connected so that one's collector drives the other's base.

The two parasitic transistors $Q_n$ and $Q_p$ are normally in the off state. If one of the two transistors is brought into the on state, and if the current gain product $\beta_n\beta_p$ is sufficiently high, latch-up occurs. Both transistors remain in the on state until the device burns out or the power supply is turned off.

Even if latch-up has been extensively studied, it can still represent a problem in the CMOS technologies used in the automotive environment because

1) supply line transients and electrical noise can give rise to parasitic currents that can turn on the parasitic transistors, thus triggering latch-up;
2) latch-up hardness is reduced as the temperature increases;
3) mixed bipolar CMOS technologies may be more sensitive to this phenomenon; and
4) the design of smart-power integrated circuits, which couple high-density CMOS logic with power devices can be quite challenging to ensure immunity from latch-up due to the large voltage swings and high chip temperatures.[8]

To avoid the latch-up problem, we usually implement and electrically characterize special "four-stripe" test structures. These structures mimic the typical layout configurations present in the VLSI (very large scale integration) CMOS technology to be characterized. We can evaluate latch-up sensitivity by measuring the value of the "triggering" current, which has to be injected into I/O lines to turn on the phenomenon.

We can increase latch-up hardness by adopting guard rings, which lower the resistances of substrate and well, shunting the base-emitter junctions of parasitic bipolar transistors (Figure 7b,c). Substrate resistance can be also lowered using a P/P+ epitaxial substrate. Triggering currents higher than 250 mA have been obtained on epitaxial structures with N+ guard rings.

In a finished CMOS IC in which millions of parasitic elements are present, identifying the latch-up site responsible

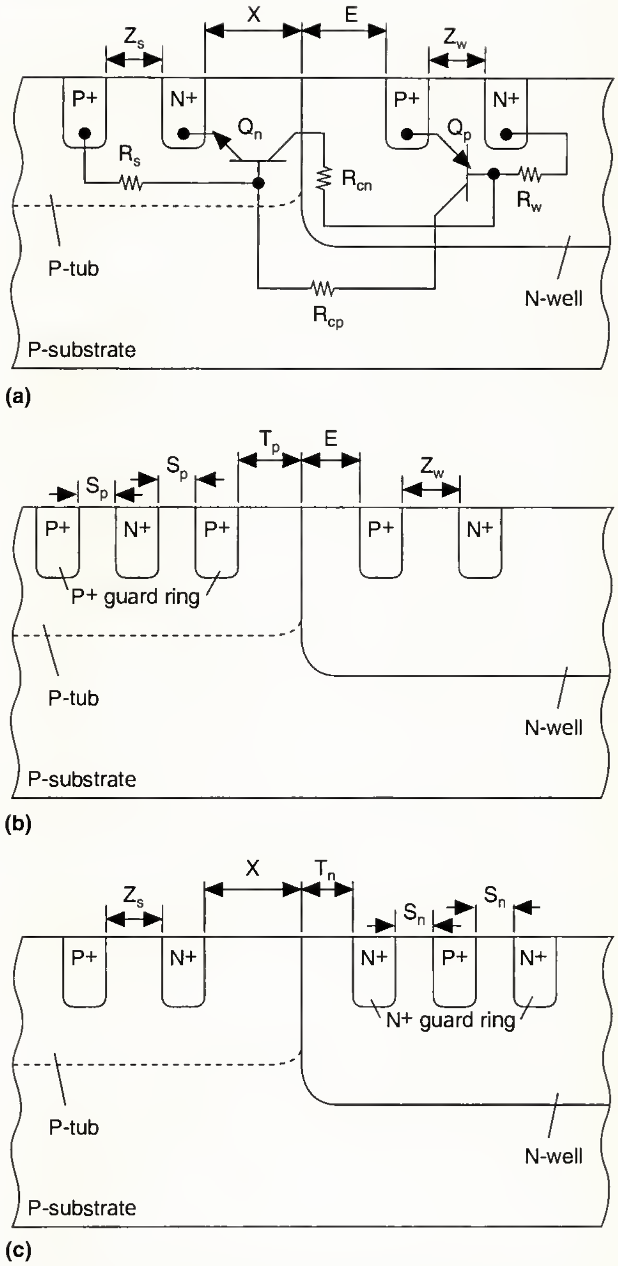


Figure 7. Schematic cross section of latch-up test structure: without guard rings (a), with P+ guard rings in the substrate (b), and with N+ guard rings in the N-well (c).

for circuit malfunctioning can still be easy, if a suitable microscopic technique is adopted. Emission microscopy can detect the infrared light emitted by the forward-biased parasitic transistors due to electron-hole recombination and directly

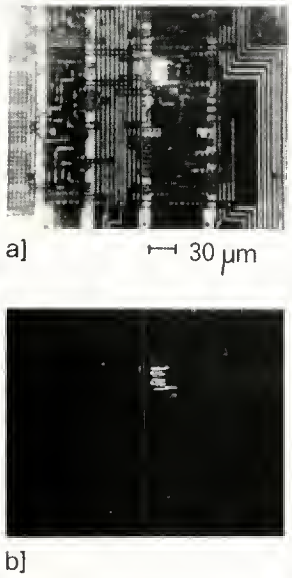


Figure 8. Emission micrography image of a CMOS device in latch-up condition: with topography superimposed (a) and with infrared emission only (b).

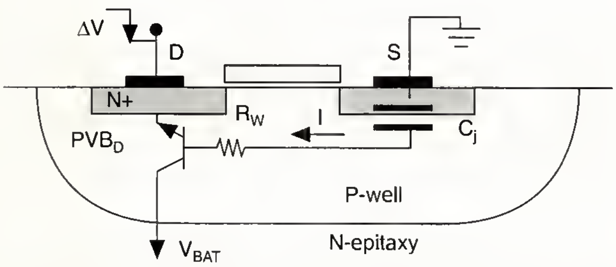


Figure 9. Floating-well concept to avoid latch-up.[11]

point out the failure site.[9] The active parasitic transistors will appear bright in an emission micrograph of the device, biased in the latch-up condition. Figure 8 shows an example in a CMOS EEPROM chip. In Figure 8a the optical micrograph of the device is suprimposed on the infrared emission image; Figure 8b shows infrared emission only. CMOS circuits free of latch-up can be achieved by decoupling the parasitic bipolar transistors using SOI technologies. LAAS CNRS has developed a design methodology based on a floating-well CMOS configuration that prevents latch-up in direct current and transient conditions for a CMOS-compatible smart-power technology, see Figure 9. Providing the well with a two-capacitor, dynamic biasing circuit, completely avoids latch-up initiation due to power device switching or power supply transients.[10,11]

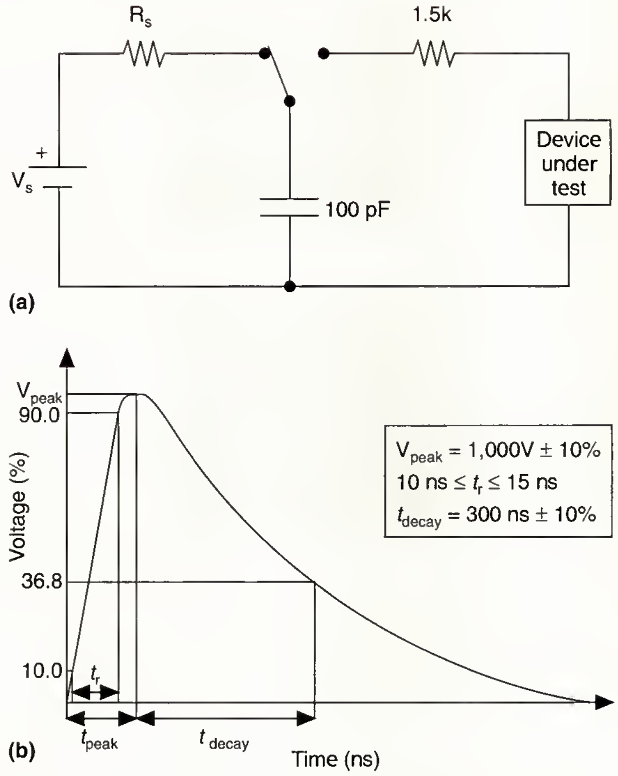


Figure 10. Equivalent circuit of test equipment adopted to simulate ESD stress according to Human Body Model (a) and ESD waveform (b).

**Failures due to electrostatic discharge.** ESD phenomena produce a reliability concern, which requires careful design of I/O structures.[12,13] Advanced process and device structures may show enhanced ESD sensitivity due to the reduced dimensions, decreased junction depth, and increased breakdown voltages with consequent larger power dissipation during transients. Moreover, maintenance of the electronic systems in the car cannot always be performed while taking all precautions to avoid the risk of ESD.

One possible mechanism of ESD involves a charged body (person working on the line) that discharges through a conductive path into the device (at ground). This most common and completely specified model is known as the Human Body Model; Figure 10a shows its equivalent circuit. The circuit consists of a 100-pF capacitor, which discharges through a 1,500-ohm resistor into the device under test; Figure 10b shows the corresponding waveform.

The research group at Tecnopolis-CSATA together with SGS-Thomson and the University of Padua has studied ESD effects in high-voltage ($V_{DS}$ up to 100V) NMOS and PMOS transistors compatible with CMOS architectures.[13] They developed and tested the following three structures:

- PMOS dual-gate transistors with a P-well drain extension structure; Figure 11 depicts a schematic cross section.
- MOS dual-gate transistors with an N-well drain extension. The device section is the same as in Figure 11, with reverse doping.
- MOS transistors implemented within this same process, using a P insulation implant as the lightly doped drain

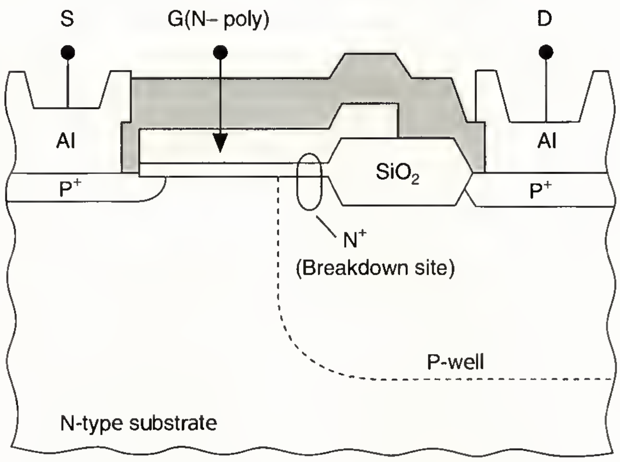


Figure 11. Schematic cross section of the PMOS transistor submitted to ESD testing with the N/P junction induced by ESD between gate and drain.

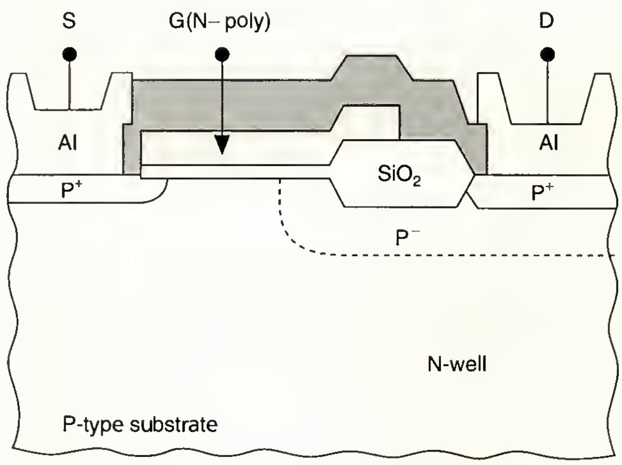


Figure 12. Schematic cross section of the PMOS implemented using the standard P-channel stopper as lightly doped drain regions.

region, that is, adopting the standard P-channel stopper as the drain extension; see Figure 12.

Output transistors were submitted to ESD according to the Human Body Model. They consisted of positive and negative pulses applied to the drain, with source and bulk connected to ground, and the gate grounded through a 1-Mohm resistance. Observed failure modes are

- for PMOS devices, a rectifying junction created between gate (N) and drain (P), see Figure 11, and a parasitic bipolar transistor between gate (N), drain (P), and substrate (N); and
- for NMOS devices, a resistive shunt between gate and source, and a rectifying contact between gate and drain. Threshold voltages for ESD failure are in the 2,500-3,000V range.

To analyze failure, researchers adopted a special Optical Beam Induced Current (OBIC) technique implemented in a laser scanning microscope. Figure 13 is a sketch of the experimental setup employed for OBIC analysis. A scanning laser beam generates electron-hole pairs within the semiconductor. The electric field originated by P-N junctions separates pairs, giving rise to the OBIC current, which is used as the brightness signal on a CRT.

By collecting the signal between the gate and the other electrodes, the sites where a junction has been created or can be accessed due to the failure will appear either bright or dark according to junction polarity. This lets us identify the failure site. Figure 14a shows the OBIC image of a failed PMOS transistor, obtained by connecting the amplifier between drain and bulk. The OBIC signal is collected evenly across the junction, as no defect is present in this area. On the contrary, when the OBIC amplifier is connected between gate and drain (Figure 14b), the signal can be collected only where a P-N junction has been formed, due to ESD, similar to correspondence of the oxide breakdown site between gate and P-well, schematically shown in Figures 11 and 13.

The same research group has studied ESD protection networks suitable for DMOS power transistors[12] and based on lateral NPN transistors or zener diodes (Figure 15, next page). They found that lateral NPN transistors failed at ESD voltages between 2,400V and 3,200V and took emission microscopy images[9] of the failed devices after each step stress.

Figure 16a, next page, shows the emission micrograph of an unstressed NPN lateral transistor biased with a reverse current of 5 µA (in breakdown condition). As can be seen, the emission is evenly distributed and corresponds to the NPN collector-base junction. If a similar micrograph is taken at the same reverse current in the device after the 2,400V ESD stress (Figure 16b), we can see an emission spot that corresponds to the failure site. The dynamic behavior of the tested structure was studied by applying a repetitive, nondestructive square

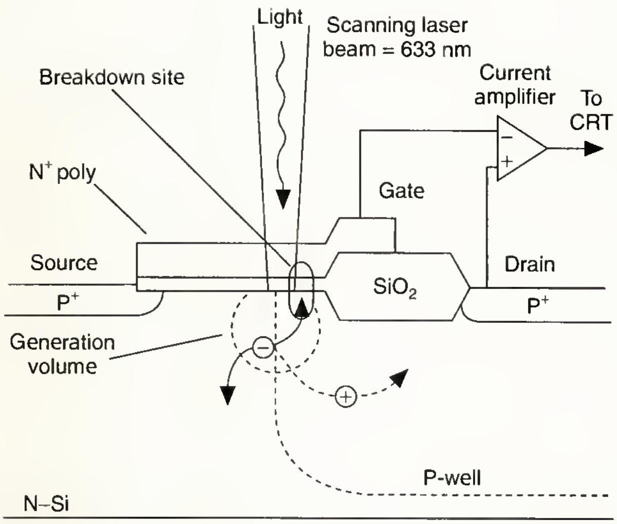


Figure 13. Sketch of the experimental apparatus employed for OBIC analysis of a failed PMOS device.

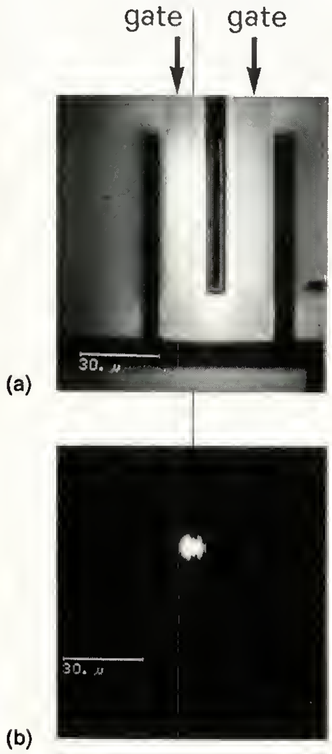


Figure 14. OBIC image of the failed output transistor with OBIC amplifier connected between drain and bulk (a) and gate and drain (b). The white spots correspond to the gate oxide defect induced by ESD.

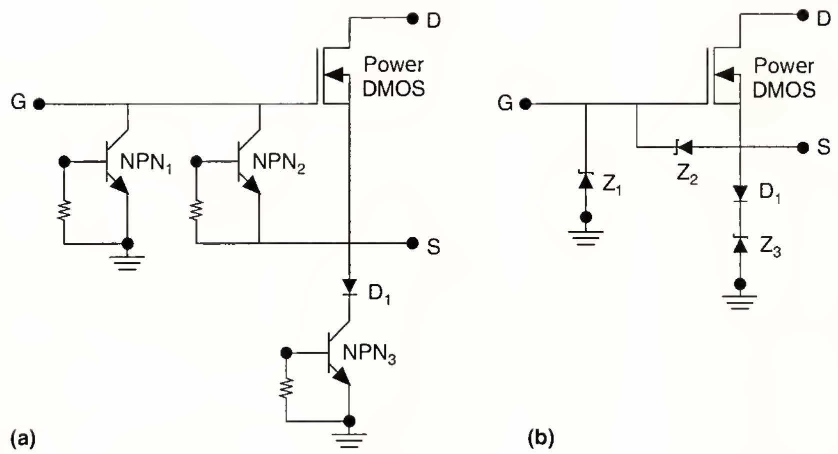


Figure 15. ESD protection networks studied for the DMOS transistor: lateral NPN transistors (a) and zener diodes (b).

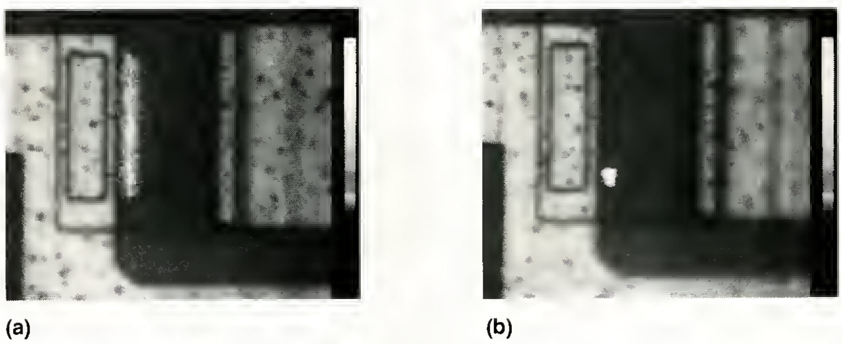


Figure 16. Emission micrograph of a lateral NPN transistor biased with a reverse current of 5 µA in breakdown conditions (a) and after 2,400V ESD stress (b). The spot corresponds to the junction failure site.

voltage pulse to the transistor. The dynamic emission image taken in these conditions, Figure 17, demonstrates that during the pulse most of the current is focused at the BE junction corners, due to the local enhancement of the electric field. This explains the failure location observed in Figure 16b.

The zener protection structure shows a better ESD hardness than the NPN one; in fact, failures are induced only for voltages higher than 4,000V. Moreover, when zener diodes are connected in the network, researchers did not observe failures (either in the protection diodes or in the DMOS transistor) up to 5,000V in the ESD test.

Another ESD model assumes that, during the ESD event, the electrical charge previously accumulated on the device is discharged to ground, thus damaging the device. Grube, Dudek, and Braun at IMS Stuttgart have designed more than 50 I/O protection structures against ESD and load-dump transients, and have tested them according to the described "charged-device" model. Optimized structures having increased ESD hardness have been identified.

The group of Flohrs and Michel at Robert Bosch GmbH has designed a voltage-protected supply input of a smart-ignition coil driver for automotive applications. The power stage switches itself off at voltages exceeding 30V, and it is protected against positive and negative transients on the supply line of an automobile. This research group is currently working on the design of smart-power switches that include diagnostic functions and enable easier fault detection and increased safety against failures.

**IC susceptibility to electromagnetic interference.** The susceptibility of automotive electronics to EMI can represent a serious threat to the correct operation of electronic systems. Within the car, electronic systems coexist with electrical devices (such as switches, relays, motors, and actuators) that can produce various kinds of electrical noise. This noise can be conveyed on supply and signal lines, forcing electronic circuits to operate incorrectly. Moreover, lightning events, radio and TV transmitters, and radar systems are sources of intense electromagnetic radiation; we can encounter one of these sources when driving close to an airport or a long-distance broadcasting station.

If the RF signals are extremely intense, electronic devices can even fail catastrophically due to the induced temperature rise. In this case, several failure mechanisms such as metal-semiconductor interdiffusion and short-circuiting of shallow junctions in ICs can be induced. Less intense signals can bring about temporary circuit malfunctioning. Since the experimental characterization of these effects on the electronic systems mounted in a car is extremely difficult, researchers are trying to develop modeling and testing techniques to evaluate EMI effects on relatively simple circuit elements. The results can be used to improve system and device design to reduce susceptibility to EMI.

The problem can be divided into two tasks. First we evalu-

ate the coupling between the incoming radiation and the car electronic system to determine how much interfering power is conducted into the terminals of the ICs employed. Then we need to evaluate the susceptibility of each IC to conducted radiation, that is, to signals directly applied to device I/O and supply lines. The first task requires extended experimental characterization of the different sources of electromagnetic noise to which the car can be subjected. The second problem has been analyzed by several researchers, starting from the publication of the *IC Susceptibility Handbook* developed by the US National Aeronautics and Space Administration and McDonnell Douglas in 1978.[14]

Pozzolo and coworkers at the Politecnico di Torino in Italy studied the susceptibility of ICs for automotive applications to EMI. They aimed to develop design tools that take into account EMI problems during the development phase of new electronic products. They studied the susceptibility of active devices to EMI by

- making measurements on different devices to find the power level of the interference signal required to have susceptibility at the different frequencies; and
- defining suitable models for the active devices, which enable a simulation of the device behavior in the presence of an interference signal to be performed.

Simulating the effect of electromagnetic interference on ICs gives us information about the more important parameters so we can design devices with high immunity.[15,16]

To study the susceptibility problem at printed board and device levels, researchers have developed models both for bipolar junction transistors and for field-effect devices. These models describe the behavior of devices subjected to conducted EMI at device terminals; in this way, a single linear simulation substitutes several nonlinear analyses in the time domain. A complete macro model for the study of the susceptibility of operational amplifiers to EMI has been developed.

The authors also characterized the filtering action of different packages and mounting techniques by exploiting the time domain capabilities of a network analyzer. The technique has proved to be very useful in separating the influence of printed board interconnections from the circuit model of the package interconnections and bonding. Several experiments were carried out on operation amplifiers with different packages, confirming the validity of the approach.

**Developing high- and medium-voltage MOS technologies.** Several applications of automotive electronics, ranging from display drivers to intelligent power actuators for multiplex wiring systems, require the development of reliable power MOS devices. These MOS devices must withstand drain voltages in the 10-200V region. Several groups within PRO-CHIP have therefore studied the performance and the reliability of high- and medium-voltage MOS transistors.

Figure 17. Dynamic emission micrograph taken when a positive square voltage is applied to the tested lateral NPN transistor.

Different approaches have been followed. Bafleur and coworkers at LAAS-CNRS have developed an N-channel vertical DMOS technology on an N epitaxial layer whose thickness is related to the device's voltage-handling capability (10 μm for 60V), compatible with a CMOS process. This technology adopts a floating-well concept with capacitance coupling to reduce latch-up, and a low-doped drain technology for the low-voltage NMOS and PMOS transistors. This technology also reduces the electric field in the channel region, thus limiting hot-electron effects and improving breakdown voltages.[17,18] The group is currently working toward the integration of an electrical motor control circuit for automotive applications in BiCMOS technology.

Ifström and coworkers at IMS Stuttgart used thermal bonding of oxidized wafers to obtain a high-quality SOI substrate, useful both for electronics and sensor applications. With this substrate, self-isolated lateral and vertical DMOS transistors can be achieved (Figure 18).[19,20] A smart-power process containing 150V, 0.8-μm VDMOS, 2-μm CMOS and bipolar devices with full dielectric isolation on fusion-bonded SOI has been developed. Vertical power devices can be obtained by silicon direct bonding of $Si_3N_4$ to $SiO_2$, exploiting the bonded nitride layer as a selective etch stop. Despite not passivating the surface, a breakdown voltage of over 500V was obtained.

SOI technologies improve device reliability in different ways:

- dielectric isolation enables latch-up to be avoided completely, at least in buffer stages;

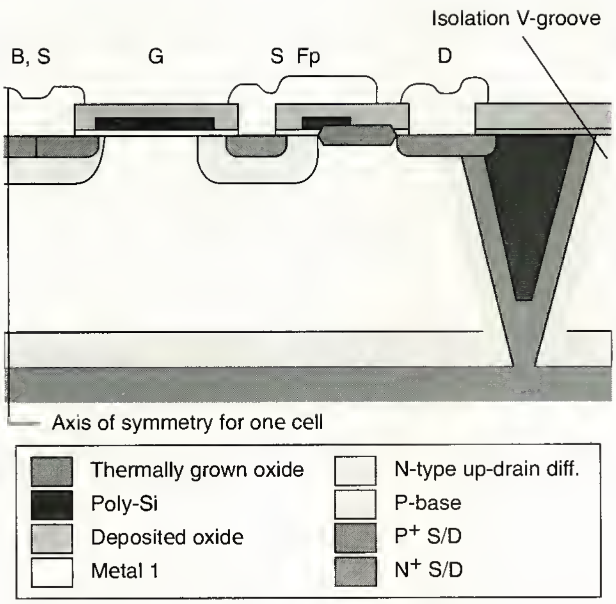


Figure 18. Cross section of a VDMOS transistor implemented in thin SOI with the direct bonding technique.

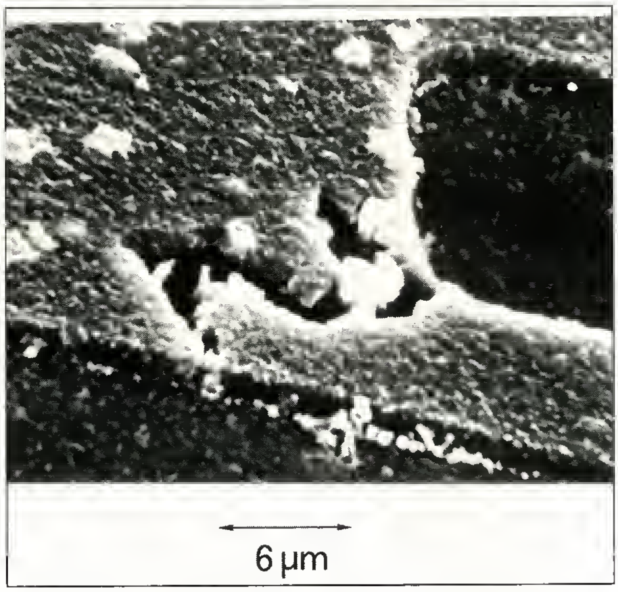


Figure 19. Void in the AlCuSi metallization of an emitter-coupled-logic IC induced by electromigration.

- the leakage current is reduced, making low-level operation at elevated temperatures possible; and
- the management of parasitics is simplified.

**Electromigration.** Electromigration can be a significant cause of failure in metallic films used as interconnections in electronic circuits. Due to the interaction with flowing electrons, the atoms of the IC metallization tend to migrate toward the positive end of the conductor. If this material transport is not homogeneous, creation of voids and material pile up can occur, resulting in open circuits, as shown in Figure 19, or in short-circuiting between overimposed metal layers. The continuing trend toward scaling down device dimensions has led to a drastic reduction in the metal line sections and in contact areas, increasing the risk of electromigration, which is accelerated by high current densities.

The OBIC technique previously described can also be successfully applied to the study of supply metal interruptions due to corrosion or electromigration in complex ICs. In this case the electron-hole pairs generated by the scanning laser beam are separated by the drain (source) junctions of MOS transistors. The $V_{DD}$ and $V_{SS}$ contacts collect the generated carriers. A current can therefore be detected by the OBIC amplifier connected at the supply terminals, thus generating a contrast in the OBIC image. Those device regions with supply line interruptions do not contribute to the OBIC signal.

Researchers can easily identify the failure sites by comparing a failed and a functional device. An example is shown in Figure 20; the OBIC image on top refers to the unfailed device, while the micrograph below refers to a failed one. Due to an interruption in the $V_{SS}$ metal (black circle), all devices connected to the corresponding branch of the supply line are not biased and do not give rise to black contrast in the OBIC image. Because the interrupted $V_{SS}$ line only supplies the device internal RAM, automatic testing detected only a functional failure. Supply line interruptions were always found on oxide steps or where current density suddenly increases, due to the decrease in metal width, or to the presence of corners. This finding strongly suggests that electromigration has taken place in these devices. The technique enables failure sites to be quickly identified, thus cutting the costs and the time required for failure analysis of complex circuits.

**Reliability of GaAs devices.** Some interest in III-V devices for automotive applications has arisen recently for three main reasons:

- carrier frequencies around 60 GHz are envisaged in Europe for road-to-car and car-to-road transmission;
- collision avoidance radars will most probably use 76-77 GHz; and
- GaAs ICs can be operated at higher temperatures than silicon, due to the larger energy gap of GaAs with re-

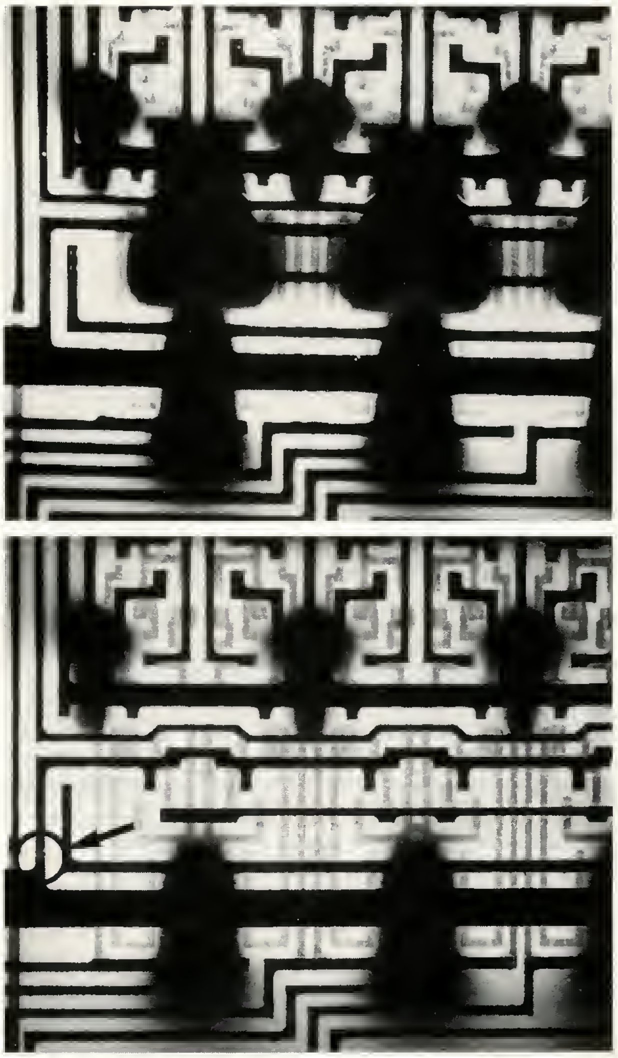

Figure 20. OBIC image of a portion of a microprocessor: unfailed samples (top) and failed sample returned from the field (bottom). The OBIC contrast reveals that the supply line is interrupted (possibly due to electromigration) in the area indicated by the black circle.

spect to silicon, even if this last advantage is partly compensated by a lower substrate thermal conductivity.

Microwave applications would possibly lead in the future to the use of low-noise and power GaAs MESFETs and high-electron mobility (heterojunction) transistors (HEMT) in the automotive environment.

The schematic cross section in Figure 21 shows the typical structure of an AlGaAs/GaAs HEMT device. In the heterostructure, the AlGaAs "donor" layer is N doped, while the GaAs layer is not intentionally doped. Electrons transfer from the wider energy-gap material (AlGaAs) into GaAs near the heterostructure interface, forming a two-dimensional electron gas (2DEG). In this way, carriers are separated from ionized impurities, thus avoiding impurity scattering and achieving higher carrier mobilities.

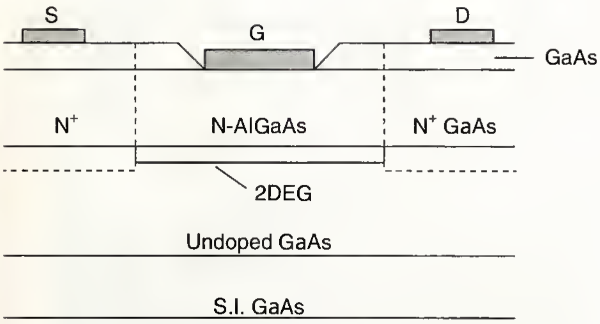


Figure 21. Schematic cross section of an AlGaAs/GaAs high electron mobility transistor (S.I. = semi-insulating.)

This fact, together with the reduced distance between the conducting channel and the gate electrode, leads to higher values of transconductance, higher operating frequencies, and better noise characteristics in HEMTs compared to MESFETs. For this reason, HEMTs are replacing conventional low-noise MESFETs in MMIC (monolithic microwave IC) technologies, and the study of their long-term stability has become relevant. In addition, critical issues are related with the stability of multilayer metallizations used for Schottky gates and ohmic contacts, the dopant redistribution in the semiconductor, and the presence of electron traps (deep levels) in the AlGaAs layer and of surface states.

The University of Padua in cooperation with Alcatel Telettra SpA has investigated the reliability of commercially available AlGaAs/GaAs HEMTs from four different suppliers by means of a storage at $T$ = 225-275°C and of biased life tests.[21] The main technological differences among the devices concern the gate metallization. Two device types (A, E) have Al/Ti gates, type B has Al/Ni gates, while supplier C adopted a gate metallization based on refractory metal silicide (Au/Pt/Ti/WSi). Figure 22 (next page) shows the cross-section transmission electron micrograph of a HEMT device with Al/Ti gate metallization.

The main failure mechanisms detected are the

- increase of Schottky barrier height of the gate diode $\Phi_B$ in devices (type B) with an Al/Ni gate;
- decrease of $\Phi_B$ in devices (type A and type E) with an Al/Ti gate; and

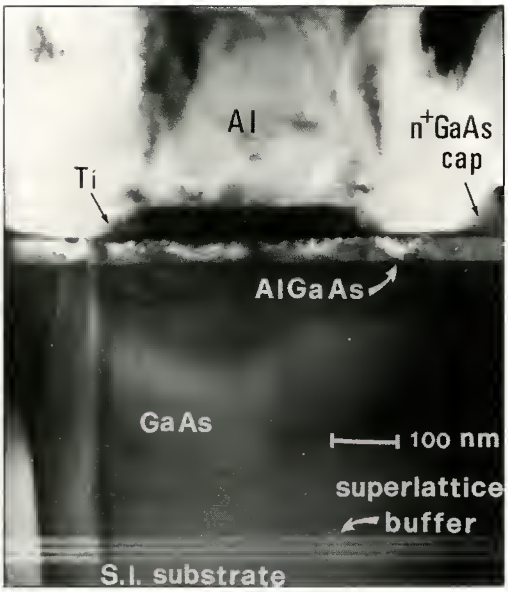


Figure 22. Cross-section transmission electron micrograph of a HEMT device with Al/Ti gate metallization.

- increase of parasitic resistances of source/drain contacts in type A and type E devices.

These failure mechanisms are thermally activated, and degradation rates have been found to be linearly proportional to the square root of annealing time. Failure times $t_f$ were found to follow an Arrhenius dependence on temperature, $t_f = A \exp(-E_a/kT)$, where $k$ is the Boltzmann constant, A is a constant, $T$ is the absolute temperature, and $E_a$ is the activation energy, characteristic of the degradation mechanism considered. Al/Ni gate contacts presented an increase of barrier height with $E_a$ = 2.0 eV, while Al/Ti gate contacts show a decrease of barrier height with $E_a$ = 1.3 eV. An increase of source and drain parasitic resistances has been detected in devices of two suppliers with $E_a$ = 1.6 eV.

To identify the physical reasons for the observed changes in $\Phi_B$, researchers adopted Auger electron spectroscopy. This technique can follow the in-depth atomic profile of the various elements that form the metal/semiconductor contact, thus detecting possible interdiffusion effects. Analyses have been performed on untreated and aged devices.

Figure 23 shows results obtained after an aging period of 3,500 hours at 275°C on Al/Ni devices as a significant example. The as-received devices showed a thin Ni film concentrated near the interface between the Al metallization and the semiconductor substrate. The Auger in-depth profile reported in Figure 23 indicates that Ni has been evenly redistributed through

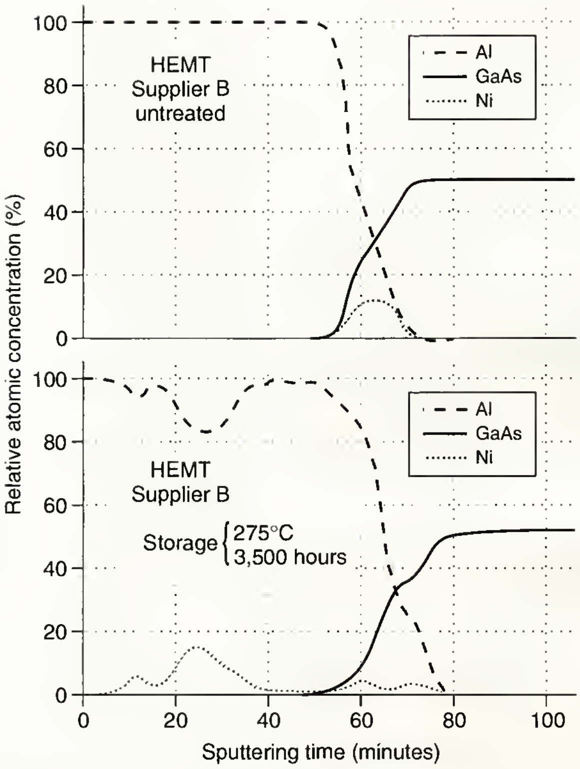


Figure 23. Auger atomic in-depth profiles of Al/Ni gate metallization in an untreated HEMT sample (top) and in one sample aged for 3,500 hours at 275°C (bottom).

the Al film during the aging test, reaching a concentration value which is barely over the detection limit of the technique (1 percent). Ni likely forms a saturated solid solution in Al. Interfacial reactions between Al and GaAs are also clearly detected, with a long Al diffusion tail into the semiconductor substrate. Reactions at the Al/GaAs interface are well-known to induce an increase of the gate diode barrier height, as observed in this case. Despite the presence of these failure mechanisms, comparison with tests on low-noise MESFETs does not show major reliability problems for heterostructure devices.

**Reliability prediction and reliability data banks.** Even if the approach of "measuring reliability" becomes obsolete as the failure rate of electronic components decreases, designers still need reference data for estimation of system reliability, calculations of cost of spare parts and of repairs, evaluation of warranty periods, and comparison of different designs. For military electronic equipment and systems, *MIL Handbook 217* is the standard for reliability predictions; however, its applicability to other environments is often discussed. In fact, even if based on a large amount of reliability data, predictions of the MIL handbook are often too conservative, leading to overesti-

mation of failure rates and to costly overdesign. New reliability models are being proposed for the new version of the handbook, and the importance of a more detailed knowledge of the physics of failure mechanisms of electronic components is being stressed in a new proposal for the standardization of reliability testing and device screening procedures.[22]

In the United States, the Society of Automotive Engineers has proposed prediction techniques for automotive applications, which can be used as a reference for general reliability evaluation of electronic components.[23] A constant failure rate $\lambda_p$ is assumed, which is calculated on the basis of a mission profile of 400 hours/year, and is directly calculated from the formula

$$\lambda_p = \lambda_b \Pi_F \Pi_S \Pi_P \Pi_T$$

where $\lambda_b$ is the basic failure rate, $\Pi_F$ is a factor identified by the component type, $\Pi_S$ is the screening factor, $\Pi_P$ is a factor identified by the package type, and $\Pi_T$ contains the temperature dependence of the failure rate. The calculation of the factor $\Pi_T$ is based on the Arrhenius law and uses activation energies that depend uniquely on the device technology (for example, 0.4eV for all digital bipolar ICs, 0.7 for all MOS logic circuits, and so on).

In Italy, the PRO-CHIP research unit at Tecnopolis is responsible for the operation of the Reliability Circle, a nonprofit organization. It is joined by the main electronic component and system makers and users, and focuses its activity on the exchange of data and experience concerning the reliability of electronic components and the related techniques. The Reliability Data Bank contains more than 3,000 reports. The Circle promotes special meetings for the exchange of information and the definition of common methodologies for quality assurance, testing, and reliability.

The researchers designed a data bank in the PRO-CHIP subproject for the collection of reliability data concerning automotive electronics. The data bank, based on SAE-defined models, allows reliability predictions according to SAE and MIL-STD models. The analysis of multisource reliability data has been performed by means of classical and Bayesian statistical approaches. It confirmed the electronic component reliability trend, especially that concerning field failure data, to be congruent with the estimates calculated by the *MIL Handbook 217F* model in standard conditions.[24]

## Fail-safe operation

Safety-critical automotive electronics tasks such as steering and braking control and collision avoidance require fail-safe or fault-tolerant components. Fail-safe operation of a system avoids the dangerous consequences of a fault by switching into a "safe" state; in other words, a fail-safe system either works correctly or is in a safe condition. A fault-tolerant system works correctly even in the presence of a fault; that is, it detects the fault and corrects the related errors. The extensive use of fail-safe or fault-tolerant techniques is not possible at this moment within automotive systems, since it would introduce excessive overhead and costs. Such use will become mandatory in the near future for critical parts and subsystems, requiring specific design techniques. Table 2 (next page) summarizes the current PRO-CHIP research in this area.

**Characterization of metastable behavior of bistable devices.** Marginal triggering conditions can place bistable devices in metastable conditions. Two types of metastability can occur: analog and oscillatory. The former causes the output of the device to stay at an electrical level near the input threshold voltage, while the latter causes the output to toggle repeatedly between the two opposite logic levels. Metastability is unavoidable, but its effects can be evaluated and limited within known bounds by using appropriate design methods. A complete understanding of the metastability is therefore an essential step in the design of devices that are intrinsically safer. Del Corso and coworkers[25] have studied oscillatory metastability, developing analytical models. These models let us understand circuit parameters and electrical conditions that trigger metastable oscillations so we can identify them and improve the resolving time of oscillations.

**Electrical and optical CAN.** A CMOS driver has been developed for the automotive controller area network (a protocol, implemented in hardware only and specially designed for automotive applications).[26] In addition to a single external component the device can withstand 120V load-dump transients, 0.33A-24V shorts, and latch-up triggering currents up to 1A, 0.1s.

An all-optical network has also been implemented, which offers very high immunity to electromagnetic interference. The adopted ring topology enables various failures to be identified; the network can tolerate faults by means of a redundant structure, coupled to supervising circuits.

**Fail-safe processor.** IMS[27] designed a fail-safe VLSI controller, minimizing area requirements by using optimized combinations of duplicated units and error coding. A structured approach lets users analyze possible hardware faults on a high level; stuck-at and bridging faults have been considered. A duplicate ALU in the controller avoids complex error coding, while RAM and ROM are implemented with error-detection mechanisms (Figure 24, next page). The processor consists of 20,000 transistors and has a peak performance of 10 MIPS at a maximum frequency of 20 MHz. Plans call for the next processor version to include on-line error detection by means of the instruction sequence check method.

IN DESCRIBING THE RELIABILITY RESEARCH ACTIVITIES within the PRO-CHIP project, we mentioned investigations of both new reliability assessment methodologies and intrin-

| Research project | Institution | In cooperation | Device/system studied | How fail-safe operation is achieved |
|---|---|---|---|---|
| Hardware for communication interfaces | Steinbeis TZ Mikroelektronik und Systemtechnik-Furtwangen, Germany | Robert Bosch GmbH | Electrical and optical controller area network | Rugged ACMOS technology; optical network with ring topology |
| Design of IC for concurrent error detection | Dip. di Ing. Elettronica, 2nd Univ. of Rome, Tor Vergata, Italy | — | Electronic subsystems | Self-checking circuits for logic; residue theory for arithmetic, correcting codes for memory |
| Fail-safe systems | Institute for Microelectronics Stuttgart, Germany | Daimler Benz AG | VLSI controllers Electr. steering demonstrator | ALU redundancy; error correction in RAM/ROM; triple redundancy with vote |
| Characterization of metastable behavior of bistable devices | Politecnico di Torino, Italy | — | Bistable devices | — |

Table 2. Fail-safe operation research groups within Prometheus PRO-CHIP.

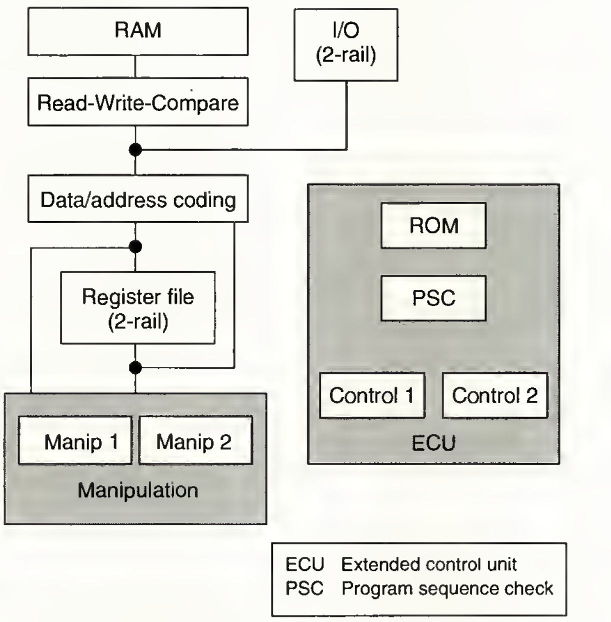


Figure 24. Minimized fail-safe system.[27]

sically reliable device technologies and designs. In particular, new I/O protection networks, smart-power devices, and fault-tolerant and fail-safe architectures are being developed, to reach the reliability requirements imposed by complex electronic systems to be used in future cars.

Other areas must be investigated to further improve safety, such as failure mechanisms and reliability of sensors and actuators; assessment of software reliability is necessary for critical applications, such as collision avoidance, automatic steering, and braking control. Rugged smart-power technologies have already found many applications within the car, and we can envisage that the use of fault-tolerant and fail-safe controllers for automotive applications will become increasingly popular in the next decade.

## Acknowledgments

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## References

1. B. Hofflinger,"The Eureka Program for European Traffic with Highest Efficiency and Unprecedented Safety (Prometheus) and Some of Its Reliability Issues," *Proc. Third European Symp. Reliability of Electron Devices, Failure Physics and Analysis (ESREF)*, vde-verlag, GmbH, Berlin und Offenbach Bismarckstrasse 33, D-1000 Berlin 12, Germany, 1992, pp. 108-110.
2. H. Herrmann, "Reliability Research in the PRO-CHIP Program of Prometheus," *Proc. ESREF,* 1992, pp. 111-131.
3. S.J. Flint and L.L. Kent, "Electronic Engine Control: Automakers Contend with One of the Harshest Application Environments," *IEEE Spectrum,* 1981, pp. 61-62.
4. J.E. Semmens and L.W. Kessler, "Nondestructive Evaluation of Thermally Shocked Plastic IC Packages Using Acoustic Microscopy," *Proc. 29th Ann. IEEE Int'l Reliabilty Symp., ISTFA*, 1991, pp. 160-166.
5. A. Hijazi et al., "Thermomechanical Failure Analysis of SMD Solder Joints," *Proc. ESREF,* 1992, pp. 327-330.
6. A. Napieralski et al., "Developing a True 3D Transient Thermal Model for Power Components or Hybrid Power Circuits," *Proc. Fourth European Conf. Power Electronics and Applications, jointly with the Symp. Materials and Devices for Power Electronics (EPE-MADEP),* 1991, pp. 104–109.
7. P. Leturcq el al., "A New Approach to Thermal Analysis of Power Devices," *IEEE Trans. Electron Devices,* 1987, pp. 1147-1156.
8. C. Canali et al., "Infrared Microscopy Study of Anomalous Latch-up Characteristics Due to Current Redistribution in Different Parasitic Paths," *IEEE Trans. Electron Devices,* 1989, pp. 969-978.
9. J. Kolzer et al., "Quantitative Emission Microscopy," *J. Applied Physics*, 1992, pp. R23-R41.
10. M. Bafleur et al., "Capacitive Coupling of Floating Body Well to Sensitive Nodes Prevents High-Resistance CMOS Circuit from Latching-up," *Electronic Letters,* 1989, pp. 860-861.
11. M.P. Vidal et al., "Floating Well-Based Design Methodology Aimed to Improve Latch-up Immunity in a Smart Power Technology," *Microelectronic Engineering,* 1992, pp. 161-164.
12. B. Bonati et al., "Analysis of ESD Protection Networks for DMOS Power Transistors by Means of Static and Time-Resolved Emission Microscopy," *Proc. ESREF,* 1992, pp. 73-76.
13. E. Zanoni et al., "Detection and Localization of Gate Oxide Shorts in MOS Transistors by Optical Beam Induced Current," *IEEE Trans. Electron Devices,* 1991, pp. 417-419.
14. McDonnell Douglas, *Integrated Circuit Susceptibility Handbook*, 1978.
15. V. Pozzolo, "Susceptibility of Integrated Circuits to Electromagnetic Interference," *Proc. Third Prometheus PRO-CHIP Workshop,* May 1990, pp. 15-38.
16. V. Pozzolo et al., "Susceptibility of ICs to EMI," *Proc. Third Prometheus PRO-CHIP Workshop,* May 1990, pp. 189-194.
17. A. Elmoznin et al., "The Smart Power High-Side Switch: Description of a Specific Technology, Its Basic Devices, and Monitoring Circuitries," *IEEE Trans. Electon Devices*, 1990, pp. 1154-1161.
18. M. Bafleur et al., "Driving and Protection Circuitry for a Smart Power MOS High-Side Switch Based on a Floating-Well Concept," *Proc. EPE-MADEP,* 1991, pp. 189-192.
19. U. Apel et al., " A 100-V Lateral DMOS Transistor with a 0.3-mm Channel in a 1-mm Silicon-Film-on-Insulator-on-Silicon," *IEEE Trans. Electron Devices,* 1991, pp. 1655-1659.
20. T. Ifström et al., "A 150-V Multiple Up-Drain VDMOS, CMOS, and Bipolar Process in Direct Bonded Silicon on Insulator on Silicon," *IEEE Electron Dev. Lett.,* Vol. EDL-13, No. 9, 1992, pp. 460-461.
21. C. Canali et al., "Reliability Aspects of AlGaAs/GaAs HEMTs," *Proc. 29th Annual IEEE Int'l Reliability Physics Symp.,* 1991, pp. 206-213.
22. G.F. Weston, "MIL Reliability: A New Approach," *IEEE Spectrum,* Aug. 1992, pp. 46-49.
23. SAE, Electronics Reliability Subcommittee, *Automotive Electronics Reliability Handbook*, AE-9, Soc. of Automotive Engineers, Warrendale, Penn., 1987.
24. M. Chirulli et al., "A Combined Statistical Analysis of Multisource Reliability Data of Electronic Components," *Proc. ESREF,* 1992, pp. 215-219.
25. L. M. Reyneri, D. Del Corso, and B. Sacco, "Oscillatory Metastability in Homogeneous and Inhomogeneous Flip-Flops," *IEEE J. Solid-State Circuits,* 1990, pp. 254-264.
26. W. Kuntz and R. Mores, "Hardware for Communication Interfaces," *Proc. Sixth Prometheus PRO-CHIP Workshop,* May 1992, pp. 168-170.
27. M. Jurczyk and T. Schwederski, "Fail-Safe Systems," *Proc. Prometheus PRO-CHIP Workshop,* May 1992, pp. 82-84.

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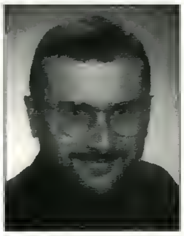

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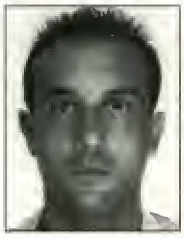

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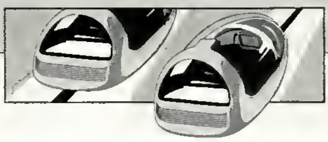

# Vision Assistance in Scenes with Extreme Contrast

**Applications of vision systems in traffic environments still suffer from the limited optical dynamic range of their sensors and lack of flexibility in readout mechanisms. We describe the performance and architecture of a High Dynamic Range Camera (HDRC) chip and the conceptional advantages for its adaptation to image processing systems.**

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*Heinz-Gerd Graf*

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*Marc E. Landgraf*

*Intel Corporation*

Several applications of image processing systems are under development within the European Prometheus project, which is a cooperative research program.[1] The task of these image processing systems is to deliver actual, well-organized, and highly reliable data to the driver but also to driver assistant systems. The assistant systems help to keep a car in its lane, recognize obstacles, or enhance visibility under certain circumstances.

If image data are to be used in vehicle control or warning systems, they must support short response times. For example, steering processes require response within some milliseconds. Imaging of high-contrast scenes with brightness changes of 100,000:1 from frame to frame is necessary for uninterrupted processing without delays. However, this is not possible with changing apertures or varying shutter or integration times.[2]

Commonly available cameras with an optical dynamic range of about 5,000:1 (74 dB), and even high-performance devices known from the literature[3,4] to reach 8,000:1 (78 dB), fall short of the minimum dynamic range of 100 dB desired in automotive applications. (This dynamic range is necessary to avoid severe saturation, caused by reflections of bright sources such as the sun.)

Some camera system approaches attain a higher dynamic range by controlling shutter, aperture, or signal integration time, but may struggle with oscillations under rapidly changing conditions. (Imagine the effects created by the shadows in a tree-lined road.) These system approaches require extra exposure control and image postprocessing hardware as well as extra time for subsequent readout and image reconstruction.

Help may come from a combination of a hardware-implemented logarithmic signal compression with a RAM-like pixel access and the opportunity to integrate such circuits together with application-specific signal postprocessors into a standard CMOS process. This approach leads to higher system performances in applications in which high scene contrast is a problem.

## Sensor architecture

During the development of the HDRC (High Dynamic Range Camera) chip, we placed special emphasis on a processor-friendly architecture. Systems engineers should be able to benefit from high optical performance as well as from an image sensor interface that is easy to adapt. Pixel processors implemented within the focal plane enlarge the application field toward imaging of extreme contrast scenes, and a RAM-like digital interface supports random access to each pixel with a minimum access time of 150 ns. A nondestructive readout mechanism allows subsequent access to the same pixel at even higher frequencies. (Figure 1 shows the HDRC64 sensor architecture, the version with 64 × 64 pixels and our prototype.)



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A maximum readout frequency of 6.6 MHz allows frame rates of above 1,600 frames/second (using the full 64×64-pixel field) but can even reach higher frame rates when accessing a smaller area of interest.

The total data rate may be further increased with a multifield architecture (see Figure 2), which supports multiple parallel outputs and therefore may serve as an input device for processor arrays.

To participate in the further scaling of technology and in design enhancements of digital macrocells, we used a standard CMOS technology as the target technology.

Table 1 lists the specifications of the HDRC64.

## Local pixel processor

This processor, which is placed around each pixel (see Figure 3, next page) within the focal plane, performs a logarithmic signal compression directly at the place of signal generation.[5] This arrangement prevents an information loss, which might occur should any of the preceding signal transport or processing circuits become saturated.

A logarithmic compression technique known from most biological systems shows some advantages concerning the dynamic range of input signals that may be processed.

The HDRC chip achieves logarithmic compression by controlled draining of the photocurrent that normally would contribute to an output voltage proportional to the irradiated power. Chamberlain first used this technique in the early 1980s.[6] A development toward higher robustness and compatibility with today's CMOS technologies resulted in a different conversion principle of the pixel processor, but it still converts an input signal to its logarithm at the pixel output. Also, the local pixel processor simplifies the implementation of area arrays by supporting full addressing capabilities to each pixel.

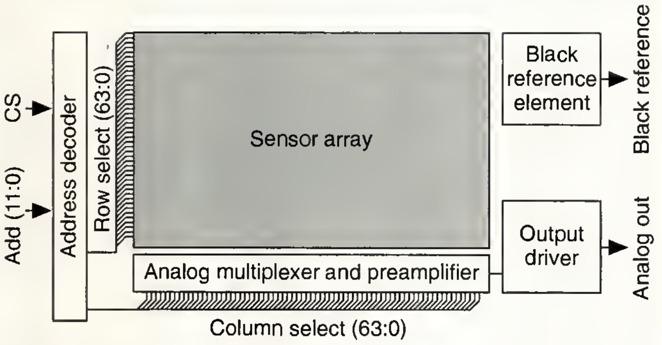


Figure 1. HDRC64 sensor architecture.

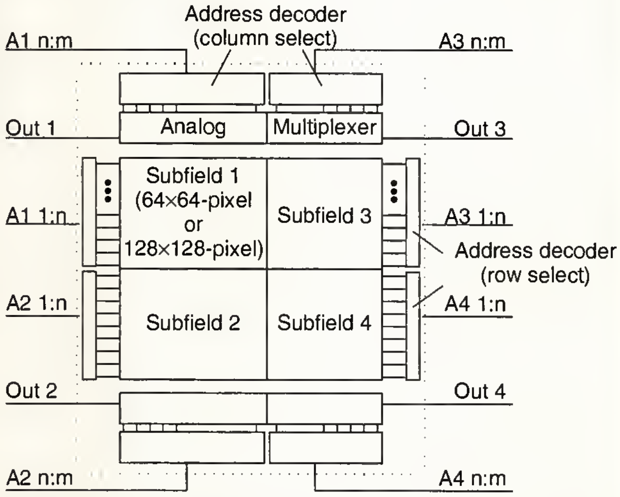


Figure 2. Multifield architecture.

**Table 1. HDRC64 specifications.**

| Parameter | Minimum | Typical | Maximum | Unit |
|---|---|---|---|---|
| Power supply + | — | 5 | — | V |
| Power supply – | — | 0 | — | V |
| Quiescent current total chip | — | 12 | — | mA |
| Operating current at 1-MHz readout frequency | — | 19 | — | mA |
| Pixel count | — | 64 × 64 | — | — |
| Total photosensitive area | — | 3.84 | — | mm² |
| Fill factor* | — | > 40 | — | % |
| Optical input signal dynamic range | — | 1:100,000 | — | — |
| Resolvable contrast | — | 10 | — | % |
| Repetitive pixel readout frequency** | DC | — | 6.6 | MHz |

*In active area ** Depends on incident power

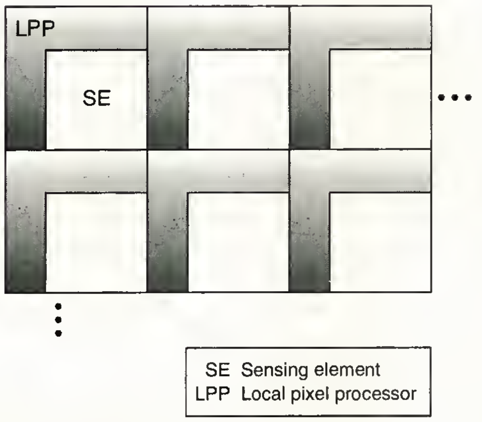


Figure 3. Sensor geometry in the focal plane.

Figure 4 shows a 2 × 3-pixel subfield. (Horizontal lines select digital rows, and vertical lines read analog data.)

Figure 5 shows the different transfer functions of a CCD (charge-coupled device) camera compared to that of an HDRC. Note that the input dynamic range that can be processed without saturation is much larger if the output signal follows a logarithmic function of the input. In Figure 5, the input signal can change its value over six orders of magnitude without saturating the HDRC device output. (That corresponds to a thermometer with a scale from 1°C to 1,000,000°C.)

The modulation of quantities like irradiated power in the space and time domains and the resolution of ratios of quantities between different pixels are even more important for image processing than the range of detected light intensities. Resolution (in the contrast and in the time and space domains) is the measure for the image quality.

The value of the above-mentioned thermometer depends on how many scale partitions one can distinguish from each

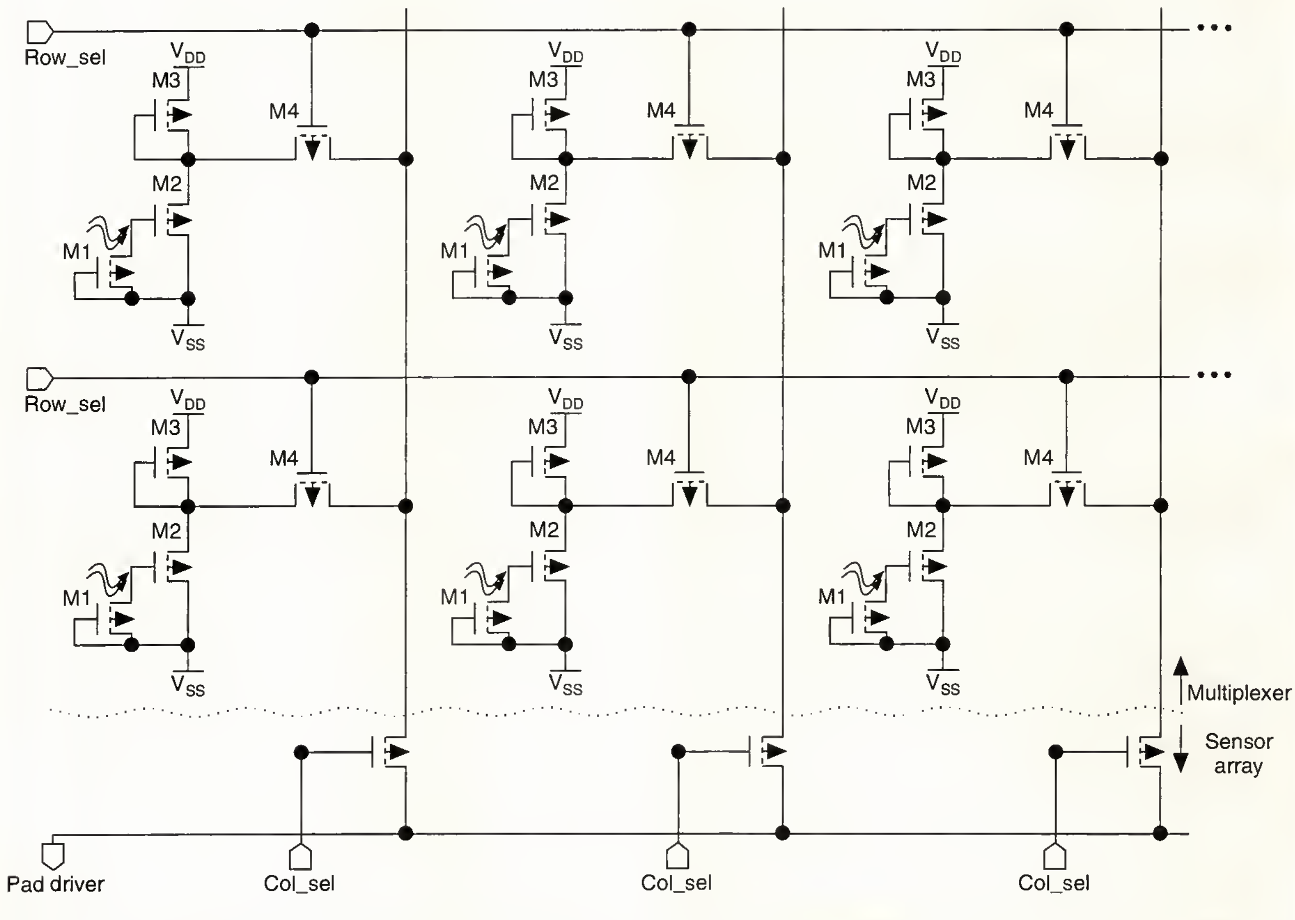


Figure 4. Circuit schematic for 3 × 2 pixels.

other; for example, whether or not you can distinguish a temperature of 100°C and 1,000°C. The thermometer's success depends on how fast it can change its value, that is, if it can react to a heat pulse within a few seconds. Thus, quality depends on the application to be met. For example, consider a high-definition video image that contains 2 megapixels, is resolved with 256 gray levels, and allows a frame rate of 100 Hz. This image, while of good quality for television applications, is not suited for high-speed imaging: The frame acquisition time is 10 ms. Also, highly dynamic scenes with contrasts exceeding a range of 1:1,000 will not be resolvable, but gray-level resolution within a given range of 1:200 (which may be displayed on TV monitors) will be superior. On the other hand, a logarithmic sensor that is optimized to handle extreme illumination conditions at the same time may not be able to resolve as many gray levels within a given range of intensities as its linear counterpart.

Figure 6 compares the contrast resolution capabilities of competing imaging systems (human eye, HDRC, and CCD camera). It is obvious that the CCD camera resolves even smaller contrasts than human eyes (at least under certain conditions). But it falls short when resolvable intensities within one scene exceed a ratio of 256:1 up to 1,024:1 (depending on the analog-to-digital converter that can be used).

HDRC imaging is thus a solution for all applications in which high contrasts must be detected at a high speed and contrast resolution of greater than 10 percent meets system requirements.

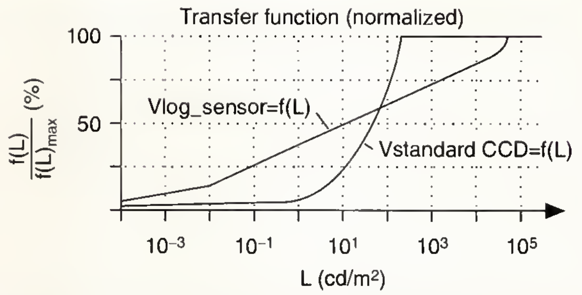


Figure 5. Transfer functions of HDRC and CCD cameras.

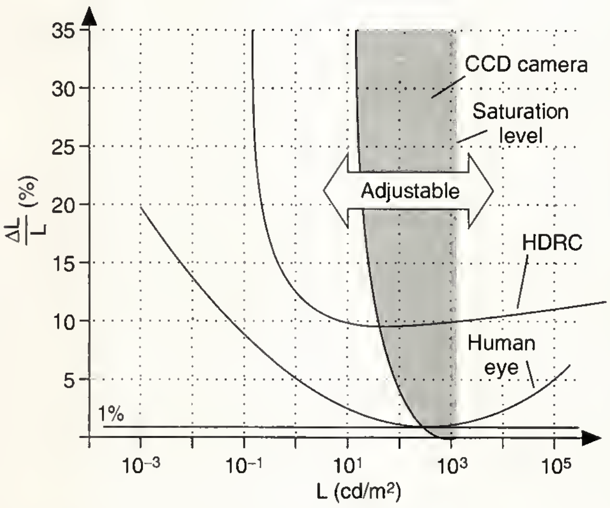


Figure 6. Contrast resolution capabilities.

## An HDRC implementation

We first integrated an HDRC chip with 64 × 64 pixels using a standard "digital" 1.2-µm CMOS technology.

Readout frequency, pixel pitch, and array size are the correlated design parameters. We chose the small array size with a medium spatial resolution (pixel pitch equals 54 µm) to get a high readout frequency. (Delay from address valid to output valid for a random access is 150 ns.)

## HDRC application

The Institut de Recherches Robert Bosch SA built an experimental camera incorporating the HDRC chip, and we interfaced it to an ITEX frame grabber board for demonstration purposes. Figures 7 and 8 (next page) show the attempts to record a critical road scene using a standard CCD video camera in comparison to using the HDRC.

The scene shows two cars meeting at a tunnel's entrance. (The left car approaches the tunnel coming out of a bright zone; the right car leaves the dark tunnel region. We placed the observing camera outside the tunnel, pointing into it.) For better comparison, we extracted a zoom window of only 64 × 64 pixels corresponding to the 64 × 64 pixels of the HDRC from a standard CCD video stream. The images from the HDRC were taken with a constant aperture setting, while the aperture of the CCD camera was set to a value that allows most details to be detected. Despite the low spatial resolution of the present HDRC, details of the cars can be extracted both in the dim and the bright regions.

In dynamic driving situations demanding short response times, the steering time for the CCD's aperture would lead to even more information loss within images taken with the CCD camera. The benefit from application of the HDRC chip in these situations is obvious and seems to be a necessary enhancement to existing vision systems in automotive applications.

## Discussion

The actual 64 × 64-pixel approach with integrated digital decoders and analog output drivers is certainly not the final "production camera" for high-speed, highly dynamic imaging systems. But it proves the functionality, and it indicates the system performance of a highly dynamic range camera feasible in today's or tomorrow's standard technologies.

Integration of a complete "microsystem" with imager, decoder, and control logic in a standard CMOS process is possible today.[7] Integration of analog-to-digital converters in a digital environment is also a state-of-the-art technique.[8] Only the used die sizes limit integration of additional digital postprocessing circuitry on chip. Spatial resolution may be increased using the same 1.2-μm CMOS technology (with no space left for digital postprocessing) and the same pixel design. The design will benefit from further scaling in CMOS technology as the factors limiting the resolution are dimensions of metal width and space.

For best system performance of an image processor, an application-specific imager solution may take system requirements into account.[9] Frame rates of above 2,000 frames/second can't be reached with a single large pixel frame but are possible by partitioning the total image frame into several subfields on one chip with a parallel readout of multiple fields.

High sensitivity (below 0.1 lux) and high gray-level resolution (greater than 8 bits) may not be reached in combination with the highest spatial resolution in planar technologies; but it is possible, if one can afford a lower spatial resolution.

Still the costs for application-specific optical integrated circuits are high, because so far there is no technology-independent support for optical standard cells. This means that every optical device must be a full-custom design. Developments in recent years show that the growing market for optical solutions will need application-specific optical ICs to overcome the problems resulting from the concentration of development efforts for image sensors (within the last 20 years) on the one and only consumer application, the video camera.

Figure 7. Road scenes taken with the HDRC.

FURTHER WORK ON HDRCs WILL FOCUS on higher spatial resolution (development of an HDRC 256 × 128 chip) as well as higher contrast resolution. New functions, such as variable conversion characteristcs or active resolution control, will take even more system aspects into account. The fact that CMOS image sensors are easy to integrate will become one major aspect in the development of vision systems. All optimizations will focus on higher system performance of camera systems or image processing systems rather than toward a singular high-performance camera chip, which could be done better in other technologies than CMOS. Therefore, our work will always be embedded in the development of application-specific image processing systems.

## Acknowledgments

We thank B. Ulmer, who accompanied our project as project leader at our sponsor company (Daimler Benz AG), for his contributions concerning the specification of the HDRC and his encouragement. We also thank J.F. Longchamp and R.

Figure 8. Road scenes taken with the CCD camera.

Cochard (at the Institut de Recherches Robert Bosch S.A., Lonay, Switzerland) for their very helpful conversations on image sensor development. Their work designing and manufacturing an experimental camera made it possible to demonstrate the performance of our HDRC chip. The staff at IMS helped with discussions on circuit simulation and design as well as with processing work for the HDRC chip.

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## References

1. B. Höfflinger,"Cooperative Research on Application-Specific Microelectronics," *Proc. IEEE,* IEEE Press, Piscataway, N.J., Vol. 77, No. 9, Sept. 1989, pp. 1390-1395.
2. R. Ginosar and Y.Y. Zeevi, "Adaptive Sensitivity/Intelligent Scan Image Sensor Chips," *Proc. SPIE*, Vol. 1001, 1988, pp. 462-468.
3. Y. Matsunaga et al.,"A High-Sensitivity MOS Photo-Transistor for Area Image Sensor," *IEEE Trans. Electron Devices*, Vol. 38, No. 5, May 1991, pp. 1044-1047.
4. J. Heynecek, "A New Device Architecture Suitable for High-Resolution and High-Performance Image Sensors," *IEEE Trans. Electron Devices*, Vol. 35, No. 5, May 1988, pp. 646-652.
5. U. Seger et al., "Development of an Image Sensor with Enhanced Dynamic Range in Standard CMOS-Technology," *Proc. Second Prometheus Workshop,* Vol. II, Institute for Microelectronics Stuttgart, Germany, 1989, p. 371.
6. S.G. Chamberlain and J. Lee, "A Novel Wide Dynamic Range Silicon Photodetector and Linear Imaging Array," *IEEE J. State Circuits*, Vol. SC-19, No. 1, Feb.1984, pp. 41-48.
7. D. Renshaw et al., "ASIC Image Sensors," *Proc. IEEE Custom Integrated Circuits Conf.*, 1990, pp. 7.3.1-7.3.4.
8. "IMS Semicustom ASICs: Gate Forest Family," Institute for Microelectronics Stuttgart, 1992.
9. J. Wyatt et al.,"The First Two Years of the MIT Vision Chip Project," private communication.

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**Marc E. Landgraf** was involved in the first HDRC design as a researcher in the IMS Interface Group. Today, he is a development engineer in the Flash Memory Development Group at Intel Corporation in Folsom, California. Landgraf received his BS degree from California Polytechnic State University, San Louis Obispo, and his MS degree in electrical engineering from the University of California, Davis.

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# Neurocontrol for Lateral Vehicle Guidance

**The complex parameterization and the nonlinear system dynamics of vehicles make the development of a controller by conventional system-theoretical methods difficult. Furthermore, this effort must be spent by experts and be repeated for each new kind of vehicle. We propose a novel solution toward autonomous lateral vehicle guidance using a neurocontroller. Neural networks can learn from measured human-driving data without knowledge of the physical car parameters. We have successfully simulated and tested this approach using an autonomous vehicle (optically steered car) on public highways.**

***Stefan Neusser***

***Jos Nijhuis***

***Lambert Spaanenburg***

***Bernd Hoefflinger***

*Institute for Microelectronics Stuttgart*

***Uwe Franke***

***Hans Fritz***

*Daimler-Benz AG*

In 1986, the European automotive industry initiated the Eureka program Prometheus (Program for European Traffic with Highest Efficiency and Unprecedented Safety). It aims to collectively develop before the year 2010 an infrastructure that would reduce the

- number of accidents per driven kilometer by 30 percent,
- travel time by 20 percent, and
- traffic-related environmental damage by 50 percent, assuming an increase in traffic density by 40 percent.

In September 1991 the first results were shown to the public on the Fiat testing grounds in Turin, Italy, as CEDs (common European demonstrators).

Autonomous vehicle guidance is one of the tasks that might be realized to increase safety and efficiency of future traffic. The Prometheus subproject PRO-GEN developed this so-called copilot function using image-processing techniques supported by extensive expert knowledge engineering. The VITA vehicle is an early example.[1]

The copilot covers a wide functionality, such as collision avoidance, lane switching, and convoy driving. A basic feature is lateral control of the car, which provides a safety resource for situations in which correct driver behavior is no longer guaranteed due to tiredness or sudden illness.

Conventional controller design methods have a disadvantage in that they require an accurate model of the vehicle; furthermore, most of them are restricted to linear systems. Unfortunately, the system dynamics of vehicles show a highly nonlinear behavior with respect to velocity. One solution to overcome this problem is gain-scheduling linearization.[2]

Another solution uses neural data processing, as this paradigm implies nonlinearity in a natural way. In addition, a neural net easily adapts to the peculiar habits of each individual driver.

Literature shows a number of attempts to cover the lateral car control task by neural techniques using simulated vehicle/road systems in which car dynamics and environmental influences are grossly simplified.[3] Recently, one neural approach used a realistic car model.[4] We will take an alternative approach and capture not the vehicle characteristics but the way the car is being handled: the control task itself. Using about 50,000 of the steering actions recorded for a "flawless" human driver on a public German highway, we captured the con-

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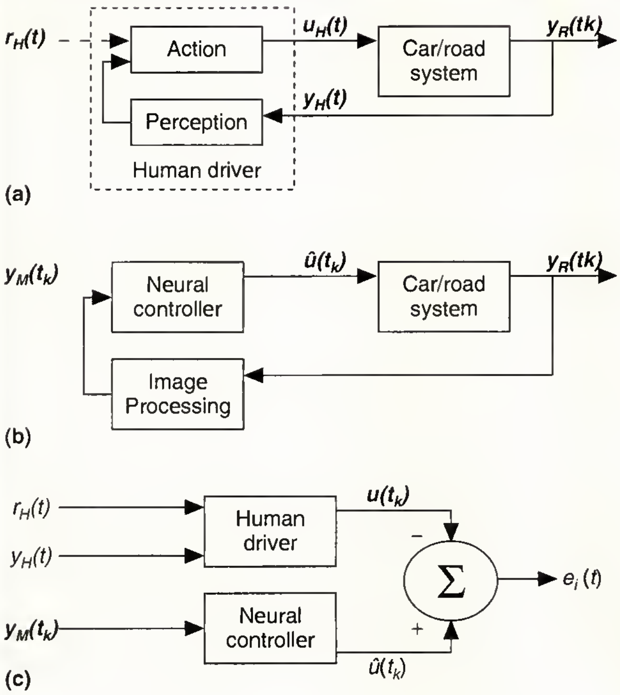


Figure 1. The general human driver/car control system with $r_H(t)$ the goal or reference inputs of the human driver, $u_H(t)$ the actuating value for the car to meet the goal inputs, and $y_H(t)$ the feedback output of the car/road system and input for the human driver (a). The neural network/car control system (b) and an identification model of the human driving behavior showing the formulation of output error (c). Only the bold variables are known.

trol task in a neural net. Subsequently, we selected a three-layer feedforward neural network with 21 neurons for this model. Finally, we installed it in the Daimler-Benz Oscar (optically steered car) vehicle for practical validation and present the first results here.

## The closed-loop system

From a system-theoretical point of view, the human driver, the car, and the road form a closed-loop control system. Figure 1a generally represents this system. The actual dimension of the situation-dependent reference input $r_H(t)$ and the car/road system output $y_H(t)$ as perceived by a human are unknown. Most published efforts regarding the human steering behavior assume $r_H(t)$ to be equal to a zero lateral offset.[3-5] However, the goal directives of the human driver depend strongly on the current traffic situation (staying in a lane, overtaking another vehicle, keeping a safe distance) and will be more in line with vague linguistic statements like: "trying to keep the car on the road" and "trying to optimize driving comfort."

Figure 1b depicts the suggested neural control system. The data the neural network accepts are limited to the information delivered by the image processing system mounted on the car. The image processing system, designed by Daimler-Benz, is based on a small transputer network. The basic algorithms running on this system are described elsewhere,[6] and its reliability has been proven in combination with conventional state space controllers.[1]

In our case, the number of used outputs of the image processing system (and thus the possible number of feedback signals) is five, namely car speed $v(t_k)$, car yaw angle $\phi_{\text{yaw}}(t_k)$, road curvature $c_{\text{ROAD}}(t_k)$, road width $y_{\text{ROAD}}(t_k)$, and the lateral deviation of the car on the road $y_{\text{OFF}}(t_k)$. The car yaw angle is the angle between the car direction and the road direction. The lateral deviation (or offset) is the distance between the car's position and the road's center line. The measured output $y_M(t_k)$ is assumed to be the neural function of these five sensory signals, although sensor uncertainty and quantization noise limit the data collection quality. The real-time image processing system evaluates 12.5 images per second and computes the relevant parameters in less than 80 ms.

In our experiments, we concentrated on the basic task of staying in a lane. Therefore, the reference input to the neural controller is not explicitly necessary, but the control target is implicitly encoded in the internal net data. Obviously, the angle of the car's steering wheel is used to effectuate the lateral deviation of the car, that is, $\hat{u}(t_k) = \phi_{SW}(t_k)$; $SW$ indicates the steering wheel angle.

Looking at both Figure 1a and Figure 1b, one can easily conclude that the problem of implementing driving behavior by a neural network can be treated as a system identification problem.[7] However, in contrast to general control approaches stated in literature, we do not identify the system to be controlled (the plant) but learn the closed-loop control task. Then, unlike normal system identification, object and model have different inputs (see Figure 1c). Equation 1 describes the assumed human driver's action: controlling only the steering angle.

$$u(t_k) = P_{\text{HUMAN}}[\,y_H(t), r_H(t)] \tag{1}$$

The objective of the neural network is to determine a function $P_{\text{NEURAL}}$ such, that $\forall t_k \in (0,N)$:

$$\begin{aligned} &\|\,u(t_k) - \hat{u}(t_k)\| = \\ &\quad \|\,P_{\text{HUMAN}}[\,y_H(t), r_H(t)] - P_{\text{NEURAL}}[\,y_M\,t_k)]\,\| \le \epsilon \end{aligned} \tag{2}$$

for some desired $\epsilon > 0$. The values for $y_H(t)$ and $r_H(t)$ remain unknown as only $u(t_k)$ and $y_M(t_k)$ are recorded. Note that Equation 2 is a sufficient condition as long as the task is to imitate the human driver. For a stable controller, however, it

is only a necessary one. In addition, one has at least to require that the net delivers an unbiased output $u(t_k)$. All networks trained during the entire development process have met this condition.

## NNSIM development environment

No detailed analytical model exists yet of the neural data processing's main advantage, identifying a plant by learning from samples. Identification requires a development environment that supports a neural network to be (re-)trained and optimized in one session without loss of data consistency. For the same reason, no loss of data consistency due to manual intervention (for instance, by file editing) can be allowed when moving the network to different realizations. This basic philosophy underlies the Neural Network Simulator.[8] NNSIM supports incremental construction, modification, and execution in automatic, interactive, and interruptible modes of operation. Of special significance is the interruptible mode, as it permits on-line changes during experimental design probing in areas where the dimensionality of the problem is not known beforehand. A global overview of the NNSIM architecture is pictured in Figure 2.

NNSIM begets its flexibility from a modular, layered software architecture, in which functionality can be enhanced incrementally by adding new functions to the procedural interface. The nature of the medium, in which the internal database is implemented (a single processor, multiprocessor, or special-purpose neural hardware), is masked by the network handler. The network handler implements the physical layer of the database and supports the construction and initialization of a network as well as simulation and import/export to other platforms. The respective procedural interfaces offer a conceptual layer to the designer. Requests, made by the standardized procedures in each procedural interface, are translated by the network handler into actions on the internal database. Therefore, every application can be created without detailed knowledge of the actual NNSIM database construction and freely moved across the various supported hardware platforms such as workstations (NNSIM_WS), personal computers (NNSIM_PC), or ASIC-based printed circuit boards (NNSIM_PCB).[9]

The menu-driven user interface offers a rich set of standard observations that have direct access to the database. This feature enhances the speed of interactive usage and does not compromise the database integrity, as observations only read the current network status. On the other hand, application-specific observations are usually guided over the standardized database access procedures. This process mainly allows a fast and secure project start without detailed knowledge of the actual NNSIM database construction. Figure 3, next page, pictures a typical NNSIM screen with a number of standard obser-

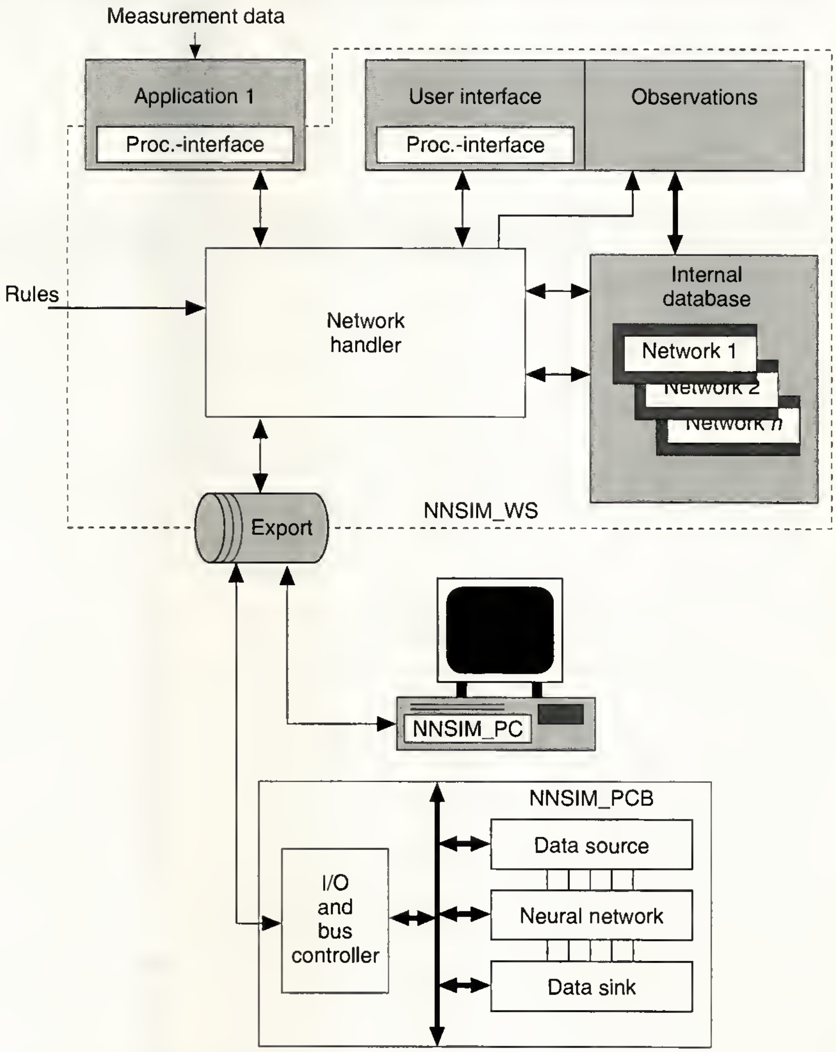


Figure 2. Architecture of the NNSIM development environment with links to PC- and PCB-level client applications.

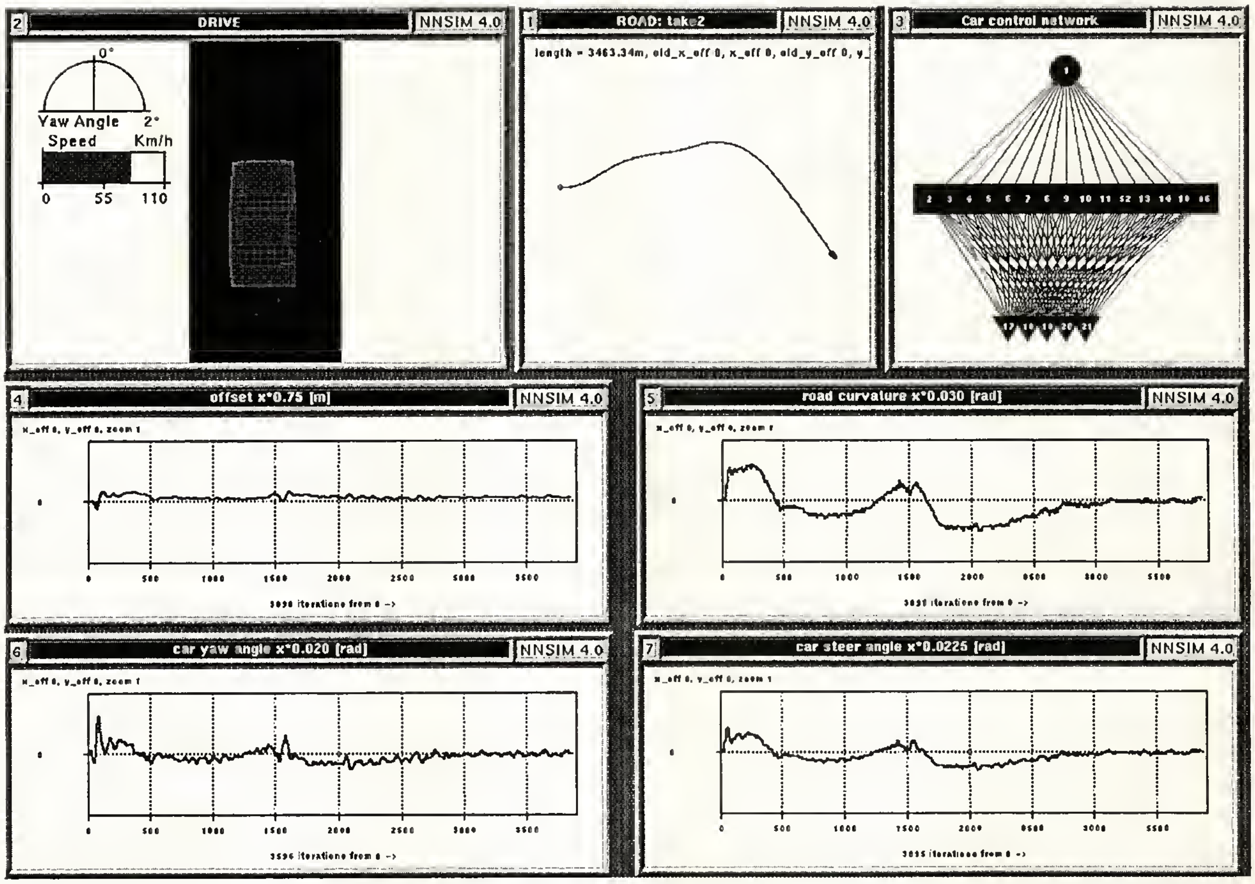


Figure 3. Typical NNSIM screen during the development of a neurocontroller.

vations and the application-specific Drive and Road windows.

In a typical design flow, the neurocontrol functionality is captured and matured at the workstation level (NNSIM_WS). If preknowledge exists, alphanumeric or graphical expert rules can initialize the network. The learning is completed from actual measurements. Artificial data are required to test the behavior of the controller in extreme situations, as these are not normally part of the measurement set.

For a first prototype test, the network is tabularized and moved to the test site, where it is included in the client application software and additional in-product fine-tuning to compensate for production spread can be performed. When the need arises, the tables can be moved back to the NNSIM environment for remedial inspection. When the network has been found to operate satisfactorily but needs further integration for reason of size and/or speed, the tables will again be returned and one or more Joplin ASICs with this same functionality are generated. This Joplin line provides digital realizations using pulse-coding techniques or Digilog arithmetic.[10]

As yet, no formal technique to prove neural functionality exists. Furthermore, neural nets are not easy to interpret; hence, there is generally a lack of confidence in the quality of a neural solution after training. We can partially solve this dilemma by providing a printed version of the neural knowledge, preferably in terms of expert rules. However, even small neural nets can comprise a vast knowledge base, which in turn leads to an extensive set of rules that must withstand thorough human inspection. Further work is required to provide a degree of structuring that enhances the transparency of the expert base.

## Designing the neurocontroller

Several data sets from different human drivers have been available to train the neural network and validate its performance. They consist of 1,750 to 6,356 measurements recorded on a German federal highway with a total driving time of 140-580 seconds. In the first investigations all measured data are scaled to the range [0,1]. These initial experiments are based

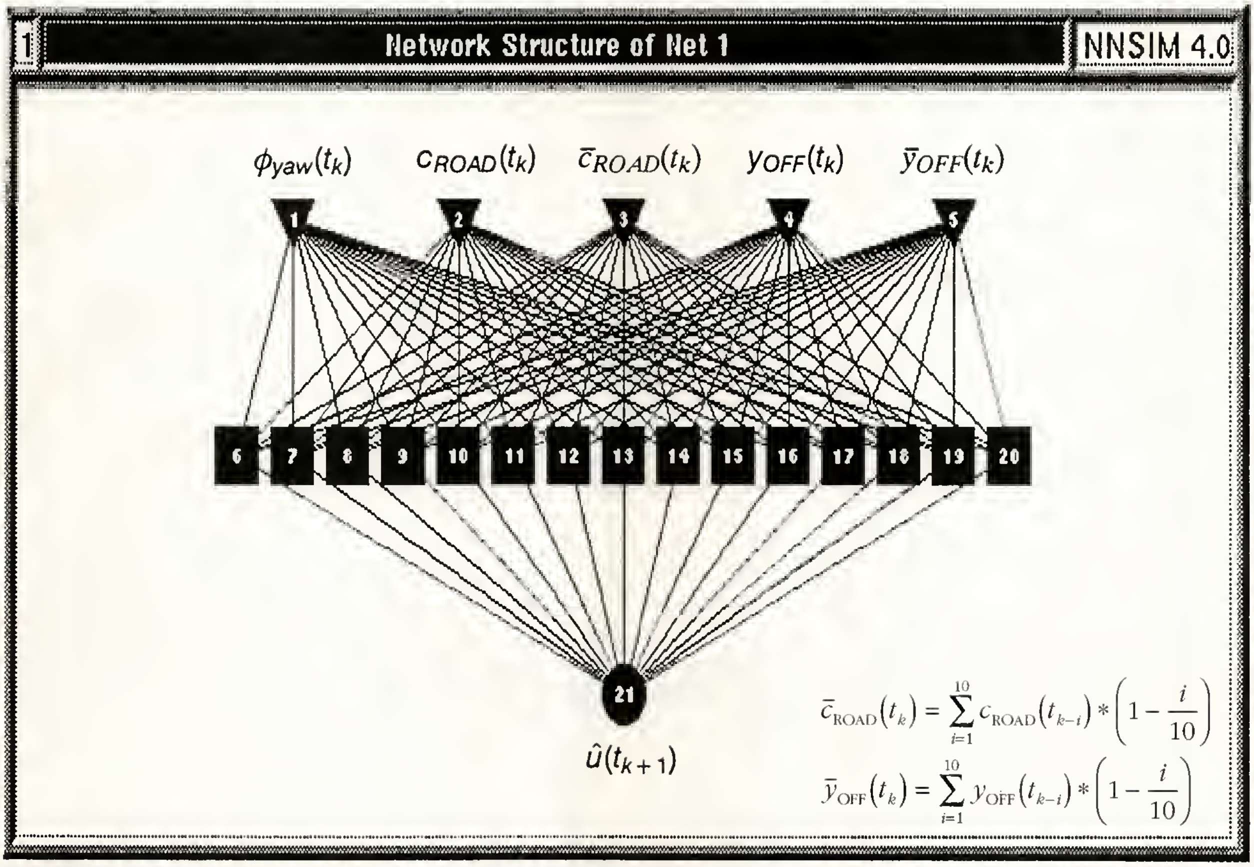


Figure 4. A small-size neural network with one output, 15 hidden neurons, and five input neurons. The network is fed with the car's yaw angle, road curvature, lateral deviation, and the time averages of both road curvature and lateral deviation.

on net structures with one hidden layer, as literature contains theoretical proof that these feedforward networks are capable of implementing any bounded continuous function $f: \mathbf{R}^n \rightarrow \mathbf{R}^m$.[11] All neurons use the sigmoid transfer function of Equation 3. The classical error back-propagation algorithm adjusts the neuron weights with the learning rate and the momentum term taken at 0.7 and 0.5 to provide a reasonable compromise between stability and speed of training.[12]

$$o_i = 1/[1 + e^{-(a_i + b_i)}] \text{ with } a_i = \Sigma\, w_{ij}\, o_j \qquad (3)$$

During these first, interruptible simulations, one can observe some correlation between the input data. A large neural net containing 50 input neurons and 135 hidden neurons learns to approximate human steering behavior. The input data contains all five measured quantities and their (up to 10) delayed values. After 100,000 learning cycles the neural net reproduces human driving actions with an average error of less than 1 percent and hardly a larger maximum error. Performing input component analysis by varying one quantity and keeping all others constant reveals some of the actual knowledge encoded in weight space. As expected, the actual output depends strongly on the road curvature, the lateral deviation, and the yaw angle of the car. Variations in car speed and lane width produce contrary effects to experienced driver knowledge, so they can be left out; their representation in the condensed learning set does not adequately reflect the physical dependencies.

With this preknowledge, the designer reduces the topology of the neural net in a second step to five input neurons and 15 neurons in one hidden layer (Figure 4). The input neurons correspond to the data signal yaw angle, road curvature, lateral deviation, and weighted time averages of road curvature and lateral deviation. This temporal memory ensures that the dynamic behavior of the vehicle can be taken into account by the net.[13] The net converges within 50,000 learning cycles to a

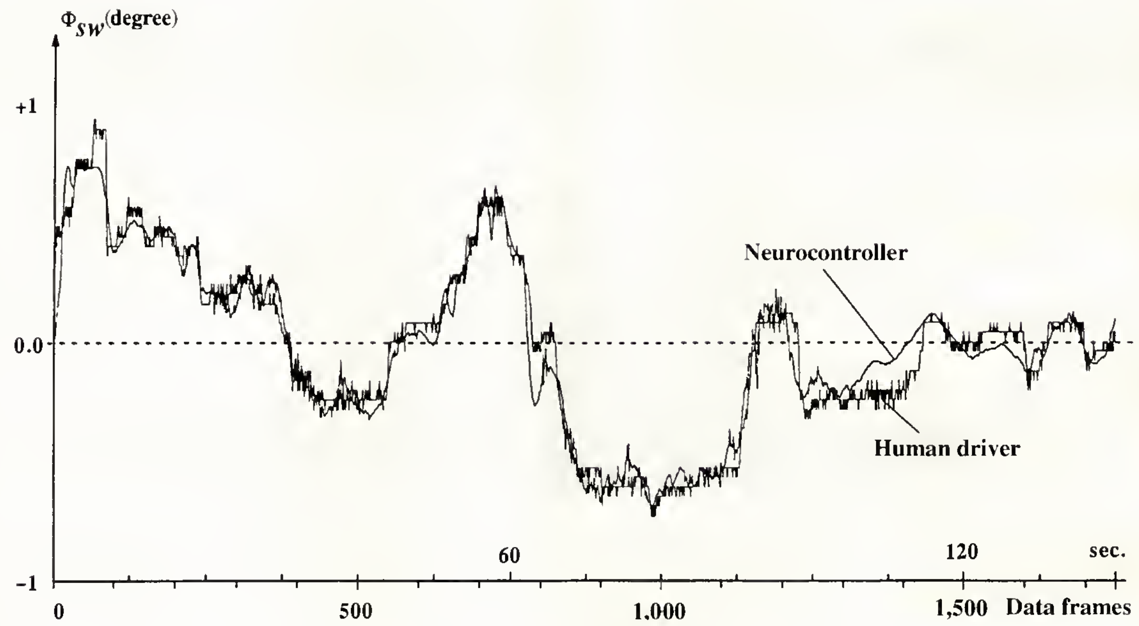


Figure 5. The steering behavior of the human driver compared with the steering behavior of the neurocontroller in Figure 4.

stable solution, whereby the input neurons are fed with one frame of measured samples during each learning cycle.

This reduced neurocontroller approximates human driver actions with an averaged error of 5 percent (see Figure 5). Looking at some parts of this diagram, we can see distinct differences in steering behavior, which might drive the vehicle off the road. Therefore the lateral control capabilities of all trained neural nets need to be investigated in a closed-loop simulation with the neural network simulator NNSIM,[8] a vehicle, and a road model. It turns out that the net uses the curvature $c_{ROAD}(t_k)$ as command variable and $y_{OFF}(t_k)$ as the variable to be controlled by the feedback loop. The values $\phi_{yaw}(t_k)$, $\overline{c}_{ROAD}(t_k)$ and $\overline{y}_{OFF}(t_k)$ control the dynamics of the car and dampen oscillations.

Experiments with different initial weight settings, numbers of hidden neurons, and human data sets indicate that the solution space of the network parameters is more sensitive to the learning set than dependent on the topology. But all potential solutions show an asymmetric behavior regarding left- and right-side offsets. Due to the scaling onto the interval between 0 and 1, 0 represents the maximum left offset. Multiplied with a static weight, 0 or values around 0 have no strong inhibiting or exciting influence on the neuron activity sum (see Equation 3). A second reason is that in the training phase 0 input values prevent weight modification. Therefore the net learns right-offset deviations or curves more extensively than left ones.

Thus, in a third step we chose a symmetric output function as described by Equation 4. The standard sigmoid function is scaled and shifted to yield outputs in the range [−1,1]. This kind of function overcomes the problem just discussed.

$$o_i = 2/[1 + e^{-(a_i + b_i)}] - 1 \text{ with } a_i = \Sigma\, w_{ij}\, o_j \qquad (4)$$

To make use of the full value range, we additionally replaced the sigmoid output neuron with a semilinear neuron with saturation points at −1 and 1. Figure 6a–c shows the driving behavior of the new small-size neurocontroller on a simulated road. The neurocontroller keeps the car on the road within 0.16 meters, peak-to-peak offset drift. Like the human driver, the net shows a static offset of 0.17 meters to the right-hand side. Further simulations on extreme situations reveal that the generalization capability of the net lets the controller handle offset deviations and curvatures much larger than those included in the learning set.

## Simulations and experimental results

As stated earlier, the problem of lateral vehicle guidance has also been investigated using conventional PID controllers.[4] We therefore compared the performance of the neurocontroller with that of classical ones. For this reason, the trained controller as well as a conventional approach are simulated in a closed loop using a simplified model of the

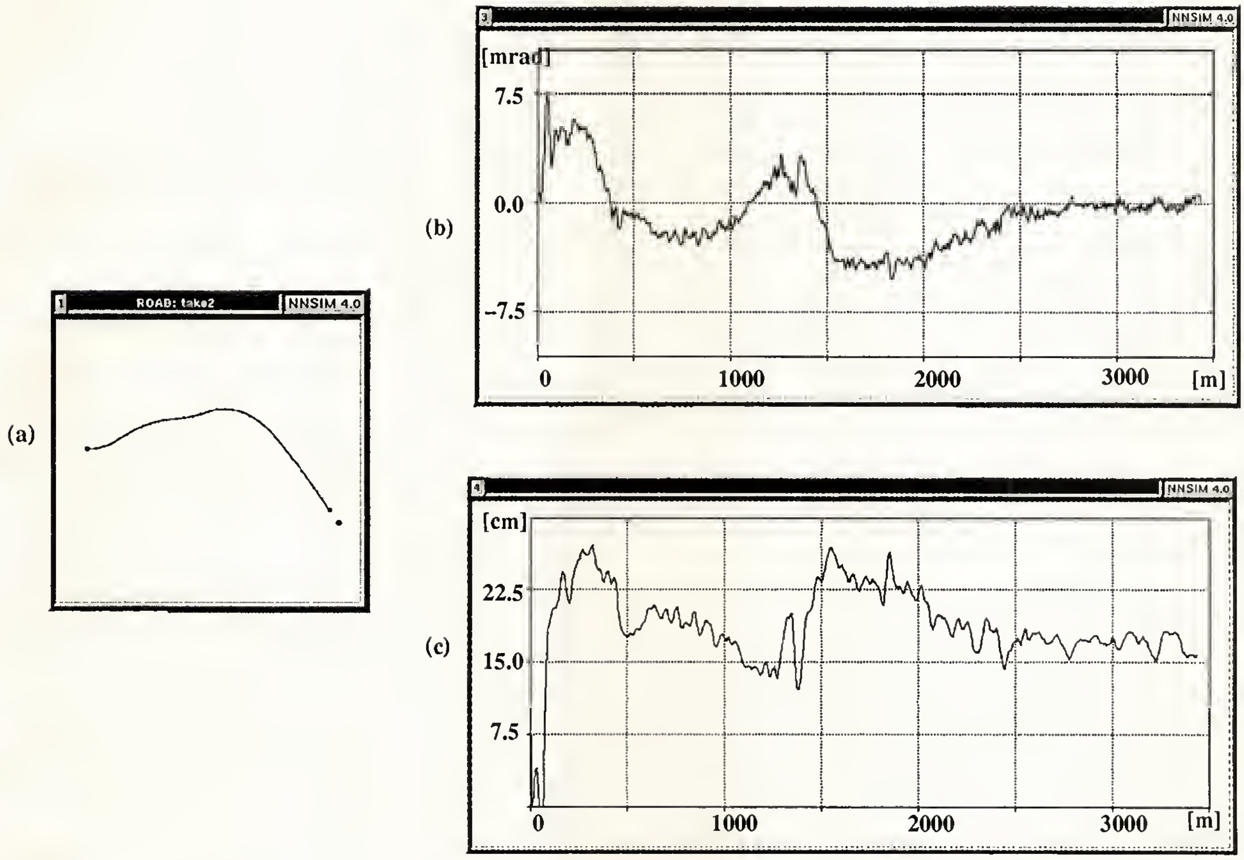


**Figure 6. Simulated driving behavior of the small-size neurocontroller at 80 km/h: part of a simulated highway (3,460-meter length) seen from a bird's eye view (a), car steering angle (b), and lateral deviation of the car (c).**

lateral vehicle dynamics. Figure 7a, next page, depicts the step response of the neural system for a lateral offset of 1 meter. The conventional linear state controller has the following four state variables: offset $y_{\mathrm{OFF}}(t_k)$, yaw angle $\phi_{\mathrm{yaw}}(t_k)$, yaw angle velocity $d[\phi_{\mathrm{yaw}}(t_k)]/dt$, and steering angle $\phi_{SW}(t_k)$. Figure 7b gives the result of this simulation.

The speed in both simulations is 25 meters/s. The neural controller shows an aperiodic behavior with respect to the offset. The remaining constant offset of 0.17 meters is caused by the tendency of the human driver in our training set to keep to the right of the lane's center. From the large slope of the steering angle at the beginning, one can see that the controller produces a large steering angle velocity. The sharp asymmetric bend of the steering angle indicates its nonlinear nature. In contrast, the linear controller shows higher order dynamic behavior, resulting in an overshoot of the offset and a larger yaw angle. If the speed is further increased, the neural controller keeps its aperiodic behavior, whereas the linear controller tends to a larger overshoot. Since there is currently no theoretical proof for stability of a neural controller, we carried out various additional simulations with different initial conditions. In all these tests the neural controller shows a satisfactory behavior.

After this preparatory work, we performed realistic experiments with a Mercedes-Benz car (300 TE) on a public highway near Stuttgart. Figure 8 represents the results for the neural controller and the conventional controller. Both diagrams show the curvature profile $c_{\mathrm{ROAD}}(t_k)$ of the part of the road we selected for the test, as well as the offset $y_{\mathrm{OFF}}(t_k)$ and yaw angle $\phi_{\mathrm{yaw}}(t_k)$. We multiplied the curvature by a factor of 100 for better visualization. Note that a curvature of 0.002 $m^{-1}$ corresponds to a radius of 500 meters, which is not typical for a modern highway but can obviously still be encountered on the older ones. Although we attempted to keep the speed constant at 80 km/h during these tests, both diagrams differ by about 3 seconds, as can be seen from the shifted curvature profile.

The surprising fact that the offset produced by both controllers has a negative mean value is caused by a strong lateral banking of the road to the left. Since this was unknown to the controllers, it acts as a permanent disturbance. Apart from this deviation, practical experiments confirm the expectations from these simulations. The excellent results of the simulations given in Figure 6, however, cannot be reached since (on actual roads) further disturbances like cross wind, grooves in the lane, badly painted markings, and so on tend to activate the system.

Obviously the neural controller produces smaller offset variations compared to the state controller. This corresponds with smaller yaw angles of the vehicle. Calculation of the yaw angle variances yields $\sigma_{yaw}$= 0.20 degree/s for the neural controller and $\sigma_{yaw}$= 0.27 degree/s for the conventional one. This behavior results from stronger steering activity, and the difference is clearly noticeable for the passenger. In all, the neurocontroller was felt to be the most comfortable of the two.

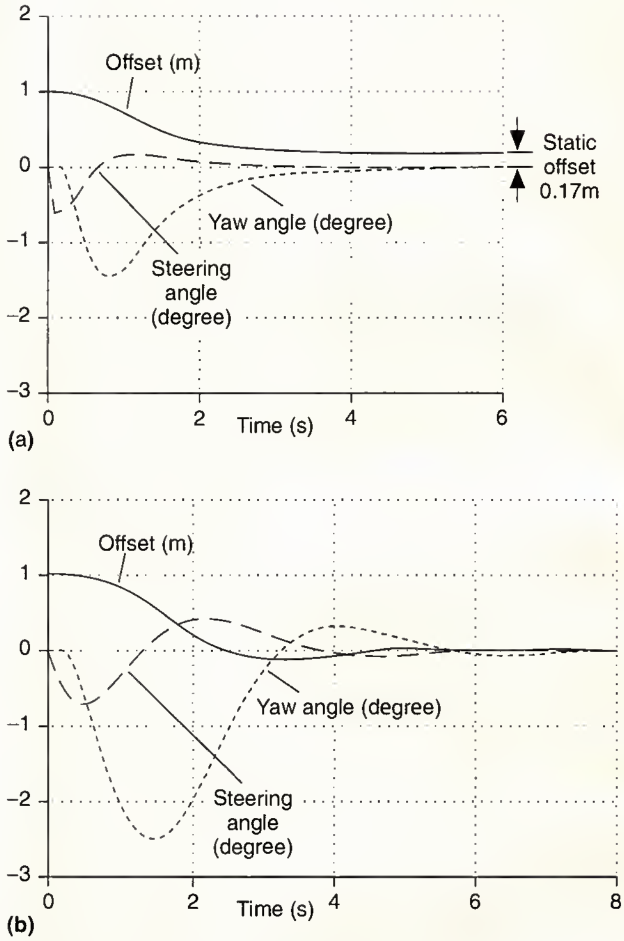


**Figure 7. Step response of both investigated controllers: neural system (a) and conventional (b).**

THE SIMULATIONS AND PRACTICAL TESTS WE DESCRIBED confirm that a small-size feedforward autonomous neural network (21 neurons) can learn to steer a vehicle at high speeds only from looking at human-driving examples. In this way, the network learns the total closed-loop behavior including the nonlinear dynamics of the vehicle as well as the driver's individual driving style. It stands to reason that the behavior to be learned should previously be proven to be correct as the neurocontroller will obviously not be capable of improving on its human example.

Besides the performance of a neural system versus a conventional one, the design effort for both approaches is a key question. Where the training algorithms for neural nets still consume much computation time, only a little knowledge of the underlying physical process is necessary. On the other hand, the design of a state controller requires a deep insight into the dynamics of the system. The conventional controller considered here was designed by experts in vehicle dynamics and control with years of experience, and the neurocontroller by the ultimate laymen.

An advantage of the classical design methods, which cannot be overlooked, is the existence of stability proofs that are valid as long as reality is adequately described by the used model. However, we are convinced that for small neural systems like the one considered here, stability can sufficiently be shown by exhaustive closed-loop simulations, which preaches in favor of neurocontrol.

The main result of our practical investigations is that the neural controller trained on human-driving examples exhibits an aperiodic behavior that does not vanish at higher speeds (tests performed up to 130 km/h). It produces less lateral deviations than the linear state controller and gives a pleasant driving feeling.


## Acknowledgments

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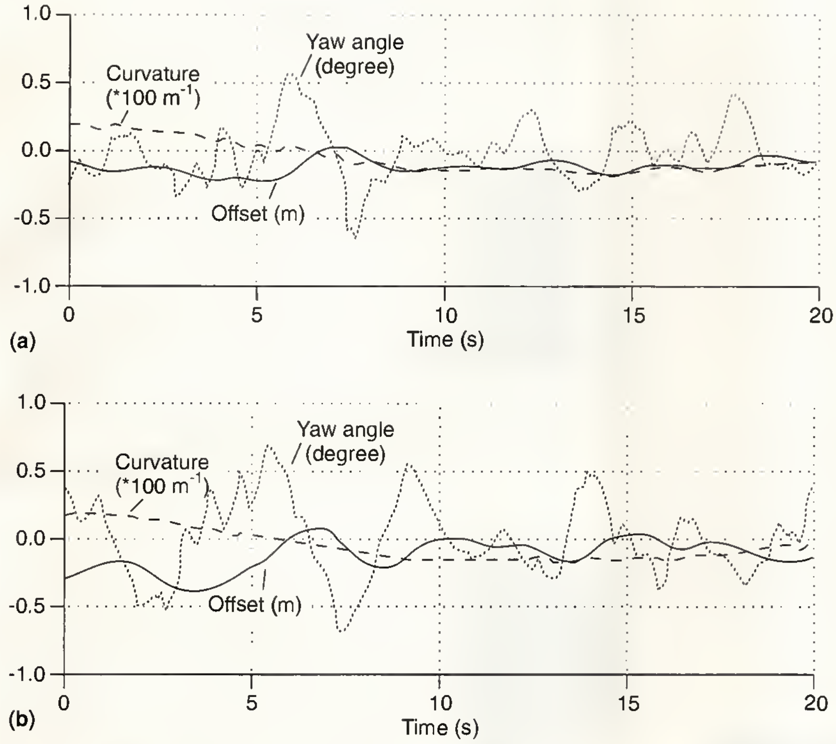


Figure 8. Experimental results for both investigated controllers: neural (a) and conventional (b).

## References


1. U. Franke, H. Fritz, and S. Mehring, "Long Distance Driving with the Daimler-Benz Autonomous Vehicle VITA," *Proc. Prometheus Workshop*, Prometheus Office, Stuttgart, Germany, Dec. 12-13, 1991, pp. 239-247.
2. E.D. Dickmanns and A. Zapp, "Autonomous High Speed Road Vehicle Guidance by Computer Vision," *Proc. 10th Int'l Federation of Automotive Control (IFAC) World Congress*, June 1987, pp. 161-164.
3. J.F. Shepanski and S.A. Macy, "Manual Training Techniques of Autonomous Systems Based on Artificial Neural Networks," *Proc. IEEE First Int'l Conf. Neural Networks*, M. Caudill and C. Butler, eds., June 21-24, 1987, pp. 697-704.
4. K. Mecklenburg et al., "Neural Control of Autonomous Vehicles," *Proc. IEEE Vehicular Technology Conf.*, May 1992, pp. 205-212.
5. R.A. Hess and A. Modjtahedzadeh, "A Control Theoretic Model of Driver Steering Behavior," *IEEE Control Systems*, Vol. 10, No. 5, Aug. 1990, pp. 3-8.
6. U. Franke, "Real-Time 3D Road Modeling for Autonomous Vehicle Guidance," *Selected Papers Seventh Scandinavian Conf. Image Analysis*, P. Johanson and S. Olsen, eds., World Scientific Publishing Company, Aalborg, Germany, 1992, pp. 316-323. Publishing Company, Aalborg, Germany, 1992, pp. 316-323.
7. K.S. Narendra and K. Parthasarathy, "Identification and Control of Dynamical Systems Using Neural Networks," *IEEE Trans. Neural Networks*, Vol. 1, No. 1, Mar. 1990, pp. 4-27.
8. J.A.G. Nijhuis et al., "NNSIM: An Environment for the Simulation of Application with Fine-Grained Parallelism," *Int'l J. Computer Simulation*, Ablex Publishing, Norwood, N.J., Vol. 2, No. 2, 1992, pp. 195-212.
9. S. Neusser et al., "Rapid Prototyping of Neural Network Applications," *IEEE Digest SPIE 92*, Mar. 1992.
10. L. Spaanenburg et al., "A Multiplier-less Digital Neural Network," *Digest Second Int'l Conf. Microelectronics of Neural Networks*, Oct. 1991, pp. 281-289.
11. K. Hornik, M. Stinchombe, and H. White, "Multilayer Feedforward Networks Are Universal Approximators," *Neural Networks*, Vol. 2, No. 5, Sept. 1989, pp. 359-366.
12. D.E. Rummelhart, G.E. Hinton, and R.J. Williams, "Learning Internal Representations by Error Propagation," *Parallel Distributed Processing*, D.E. Rummelhart and J.L. McClelland, eds., MIT Press, Cambridge, Mass., Vol. 1, 1986, pp. 318-362.
13. T. Troudet et al., "Towards Practical Control Design Using Neural Computation," *Proc. Int'l Joint Conf. Neural Networks*, Vol. II, July 8-12, 1991, pp. 675-681.


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## Reader Interest Survey

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Special Report:

# Supercomputing–the View from Japan

**Information technology is the most important area of research in Japan, with industry spending the bulk of the funds, followed by private and government research institutes and universities. To keep pace with developing information processing needs, MITI's Superspeed project investigated high-speed novel devices and computer architecture, algorithms, and languages for parallel computing.**

**David Kahaner**

US Office of Naval Research

*[David Kahaner is on assignment with the US Office of Naval Research. He generally comments on activities in the Far East for inclusion in the Software Report column. Since we felt readers would be interested in a detailed description of supercomputing trends in Japan, we also offer this special report. His comments are his own; they do not express any official policy.–Ed.]*

In Japan, information technology is the most important area of research besides life sciences and environmental research. For example, Japan's 1989 research and development budget for information processing was about ¥1,012 billion, of which ¥958 billion were spent by industry, ¥24 billion by private research institutes, ¥23 billion by universities, and ¥5 billion by governmental research institutes. (There are approximately 125 yen per US dollar.)

## Superspeed project

At the end of the 1970s, as it became apparent that future information processing needs would require new computer architectures and new devices, Japan's Ministry of International Trade and Industry (MITI) went the usual way in bringing together experts from universities, governmental research laboratories, and industry to formulate a project proposal. The outcome was quite unusual, however, as MITI decided to run two large projects in parallel; the High Speed Computing System for Scientific and Technological Uses Project, dubbed the Superspeed Project, (1981 to 1989, ¥23 billion) and the Fifth Generation Computer System Project (1982 to 1991, ¥55 billion). While the FGCS Project aimed at a risky, new computing paradigm, cutting relationships to existing computer systems, the Superspeed Project was more of an extension of the present systems. It aimed at the development of a high-speed computing system for scientific and technical applications. The target system was supposed to operate at a rate of more the 10 Gflops, which was 100 to 1,000 times faster than the speed of conventional computers at that time. Two major R&D projects were conducted: one on high-speed novel devices and one on computer architecture, algorithms, and languages for parallel computing.

The six major vertically integrated computer/semiconductor companies–Fujitsu, Hitachi, Mitsubishi, NEC, Oki, Toshiba–together with the Electrotechnical Laboratory (ETL) participated in the project. The research on high-speed devices was divided among the six participating firms: NEC, Toshiba, Hitachi, and Mitsubishi researched GaAs chips; Fujitsu, Hitachi, and NEC, Josephson junctions; Fujitsu and Oki, HEMT (high electron mobility transistor) devices.

The research on parallel processing was divided into three subgroups: a high-speed parallel (four-CPU) subproject (called Parallel, Hierarchical

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**US supercomputers have more CPUs, each having a small number of pipes. Japanese machines have had fewer CPUs, but each has more pipes.**

Intelligent computer project, or PHI); the Sigma-I dataflow subproject; and a satellite image processing subproject. Of these, PHI was the most important. In a practical approach to developing a four-CPU machine as quickly as possible, the subproject combined four of Fujitsu's existing one-processor VP2000 supercomputers. To this combination was added a large high-speed common memory. Since each of the VPs already had its own memory, the concept of a hierarchical memory structure appeared. The idea was that a user should not have to know about this hierarchy and could treat the memory as "flat."

The project was concluded in 1990 by demonstrating the PHI system to the evaluation team. The prototype high-speed parallel system using four processors ran at over 10 Gflops, peak, and had real performance of over 1 Gflops. NEC wrote and tested one benchmark that solved a very large (32K) system of linear equations in under 11 hours. This was not a prototype of a machine that could be directly commercialized. GaAs devices–HEMTs and MESFETs–were used, though not as extensively as envisioned. Josephson junction devices were not used at all, though advances in such devices put Japan in the lead in this area. Less tangibly, the project focused the private sector on supercomputers at a critical time, earlier and more heavily than they would have done individually. Of course, cooperation also meant that work was done faster and more economically. Individually, the Japanese companies were also investing heavily, and some estimates were as high as three to four times the government figure, ¥300 to ¥500 million by each of the three.

## Supercomputing

There are between 400 and 500 supercomputers installed worldwide (excluding IBM installations which are difficult to count); about 125 of these are now in Japan. Three large Japanese electronic companies, NEC, Fujitsu, and Hitachi, produce shared-memory supercomputers with some parallel features; these are products, and are supported and marketed as such. Within Japan, Fujitsu has almost half of the supercomputer installations, with Cray, Hitachi, and NEC sharing the balance.

There are about 40 supercomputers at Japanese universities, but the number could be misleading because at least a third are older machines or others with very modest performance. Most Japanese university scientists can get supercomputer time, but rarely on top-end machines which are mostly found at industrial labs or in the prestigious national universities. Access to supercomputers at Japanese universities has improved markedly in the past two or three years, though in my opinion, it is still below what is available to US academics.

Networking has improved recently, but academic networking is not as ubiquitous as it is in the US. The prestigious universities have excellent services, while many other universities have none. There are more high-performance networks in the US than in Japan. Network interconnectivity in the US is also much better than in Japan; several more or less independent Japanese networks are supported by different Ministries. Researchers in Japan sometimes communicate with each other or with colleagues in Europe by transiting through the US. Counterparts to very high performance networking projects in progress or planned in the US have not yet jelled in Japan. However, Japan has excellent, sometimes unique technology, including a large infrastructure in the ISDN, and their networking difficulties seem to be more social, organizational, or cultural than technological. Nevertheless, research in supercomputing trails that of the West, except for applications developers working on commercial software packages.

## Architecture and performance

Today's supercomputers have large memories, 1 to 32 Gbytes, and several (currently up to 16) independent and very high performance CPUs, which are sometimes called functional units or FUs. Within each CPU are several pipelines (pipes) consisting of the components that add, multiply, and so forth. (Within a CPU the pipes have only one instruction path and must all carry out the same calculation, whereas different instructions can be executing on the independent CPUs.) A floating-point operation is not achieved until the pipe has been filled, but once this happens a new floating-point operation occurs each clock cycle (hence the term pipe). Data can be moved to and from memory at rates of up to a few gigabytes per second, but this is not fast enough to keep up with the arithmetic performance. Thus some kind of memory hierarchy is employed. For example, within each CPU, data from memory first goes to registers, which are built of the fastest and most expensive static-RAM chips and have a capacity up to about 1 Mbyte. Under certain circumstances, the pipelined arithmetic units can operate on data from the registers at the peak hardware speed.

An essential difference between US and Japanese supercomputers has been that US supercomputers have more CPUs, with each having a small number of pipes. Japanese machines have had fewer CPUs, but each has more pipes—up to 16. This situation arises mostly because US companies

have more experience building multi-CPU machines, but the distinction is slowly changing as the Japanese add more CPUs to their systems.

Peak performance can be computed from the hardware specifications of the machine. It is obtained by dividing the total number of independent add and multiply pipes by the clock cycle time in nanoseconds to produce a result in gigaflops. Performance of Japanese supercomputers is always specified in terms of the peak that the hardware can achieve. Peak performance varies from about 5 Gflops for Fujitsu's VP2600 (billions of 64-bit flops) to 32 Gflops for the Hitachi S-3800. The Cray Y-MP C90 has a peak speed of about 15 Gflops. NEC's SX-3 has a peak of 26 Gflops.

Of course, most real applications will exhibit performance far below the peak. Actual performance is measured in terms of throughput, performance on specific applications or benchmarks, and other criteria. (Informally, many scientists assume that usable speed is one order of magnitude less than the claimed peak.) This rate can be heavily influenced by how rapidly and in what quantity data can be moved around. The start-up time to fill a pipe from a register is an overhead, and it will reduce the computing speed unless it can be amortized over a sufficiently large number of calculations. If there are many pipes, subdividing arrays to use them all reduces the number using each and increases the relative importance of the start-up. Also, bandwidth between memory and registers must match the realizable speed of the CPUs. There is additional overhead (memory latency) arising in the process of fetching numbers from memory for deposit in the registers; this depends on the type of memory chips used, how skillfully irregular retrievals are carried out, and whether bank or other conflicts in memory are avoided. In real problems, there are significant fractions of the program that require floating-point computation of scalars as distinguished from arrays. Some supercomputers such as Fujitsu's VP2000 have two separate scalar arithmetic units for each CPU operating concurrently with the vector (array) unit. Like data movement, these scalar units are not relevant in computing peak performance, but are important in measuring real performance.

The key to building a high-performance supercomputer is to balance memory capability, arithmetic processor performance, data movement capability, and other components. Each component plays a crucial role. This is generally related to the overall architectural design of the system, and is an area in which Cray has been particularly strong.

## Supercomputer technology

Another way to make machines faster is to use faster components, hardware, and devices, and the Japanese have excelled here. NEC states explicitly in its 1990 annual report, "... the actual performance of a supercomputer is determined by its scalar performance .... NEC's approach to supercomputer architecture is clear. Our first priority is to provide high-speed single-processor systems which have vector processing functions and are driven by the fastest technologies, while giving due consideration to ease of programming and ease of use; we also seek to provide shared memory multiprocessor systems to further improve performance." The Japanese see four major hardware tasks as being key to additional performance: faster chips, smaller size, heat reduction, and elimination of logic bugs.

**_Hitachi's 1992 supercomputer uses 25,000 gate arrays, NEC's (1989) has 20,000, Fujitsu's (also 1989) has 15,000._**

Supercomputers from NEC, Fujitsu, and Hitachi use tried and true emitter-coupled logic (ECL) semiconductor technology for basic processor chips, but have pushed their capabilities in this area quite far. For example, clock cycle times vary from 3.2 ns (Fujitsu), to 2.5 ns (NEC), to about 2.0 ns (Hitachi). These figures are better than US products (the Cray Y-MP C90 has a cycle time of 4.2 ns). Faster clocks translate into better performance. Another example of technology advance is in the area of lithography, the process of outlining circuits. Beginning as an optical process generating 10-μm line widths in the 1960s, the practice is now an X-ray process in the 0.8- to 0.5-μm range. As line widths become narrower, more highly packed chips can be built. The Japanese are aggressively working to reduce line width, and also to improve width variability in the hopes that the former will translate into direct performance improvements and the latter into less conservative designs. ECL gate densities are also improving. Hitachi's newly announced (1992) supercomputer uses 25,000 gate arrays, NEC's (introduced in late 1989) has 20,000 gate arrays, and Fujitsu's (also introduced in 1989) uses 15,000 gate arrays.

High-end Japanese machines all have water-cooled CPUs, but slightly slower air-cooled versions are also available. In addition, air cooling is used in peripheral devices. Fujitsu uses GaAs chips in some of its peripherals so these can be effectively cooled by air (GaAs can run cooler than silicon). Generally, the use of exotic device technology has been fairly conservative, although there are research projects at all the large Japanese companies. Thus far GaAs is not being used for CPU chips in any commercial Japanese machines, nor are even more sophisticated Josephson junction circuits. Fujitsu used the Superspeed Project results to develop a hybrid Josephson junction-VLSI device, and plans to use it in its next-generation supercomputers, probably out in the mid-1990s.

***There is no work in Japan on standardization of scientific software, and almost no research comparable to that in the West on portable numerical algorithms.***

(It takes three to five years to produce a large-scale supercomputer product.) Similarly, NEC developed GaAs logic devices as well as memory chips and has designed a multichip package for supercomputers. GaAs is seen as slowly replacing ECL, though the Japanese are convinced that performance gains can still be obtained with silicon.

## Supercomputer software

All three Japanese supercomputers now are available with a customized version of the Unix operating system. The use of Unix will help the migration of application programs onto Japanese systems. People are just now coming to grips with the need to assess software costs, and moving to Unix is clearly seen as one way to reduce costs. In Japan, this is a change from the use of proprietary operating systems that has occurred only in the past two or three years. For Hitachi it is only just now occurring, and the company has not totally embraced Unix. Its newest supercomputer is available in a Unix version, and also with the company's own IBM-like operating system for compatibility with older Hitachi systems. The situation is similar for Fujitsu, which also supports both Unix and its own system.

In the past, applications developed in the West have been installed very slowly, which was a major impediment to the purchase of Japanese supercomputers both in and outside Japan. Using Unix will improve this situation. However, using a standard operating system only means that software portability is improved and development time is reduced, not that a program will run efficiently. There does not yet seem to be any shortcut to maximum performance short of incorporating knowledge of the hardware into the algorithms and software.

Early Japanese supercomputer software development was limited to producing Japanese language interfaces for Western software products, and this is still an important activity. For example, NEC has recently moved the latest version of the heavily used engineering analysis system Nastran to its supercomputers, and the company's supercomputer promotional literature lists about 100 products (many from the West) that are available in a wide range of disciplines. Other vendors are engaged in similar projects. But more recently, first-rate packages designed and implemented in Japan are appearing. Good examples are:

- DEQSOL from Hitachi for the solution of the partial differential equations arising in engineering simulation,
- Alpha-flow from Fuji Research Institute for solution of fluid dynamics problems,
- Fortran/a from Fujitsu, allowing object-oriented programming from within a Fortran environment, and
- AMOSS from NEC for molecular orbital calculations.

For those users who need to create software (rather than using existing applications), standard languages such as Fortran and C are available on all Japanese supercomputers, and the vendors are careful to ensure that these meet all announced standards, although they have various enhancements too. To get efficient programs, users can rearrange their algorithms, insert special directives within their programs, and also use vendor-provided automatic vectorizers and autotasking. Optimized vendor libraries with simple interfaces are another good way to obtain efficiency. The three Japanese supercomputer companies have large teams of programmers developing these libraries, and they also support well-known commercial libraries from the West; IMSL and NAG, and noncommercial projects such as Eispack and Linpack, among others. If the user interfaces are standardized, portability is maintained along with efficiency. But there is no work originating in Japan with an eye toward standardization of scientific software. Also, there is almost no research comparable to that in the West on portable numerical algorithms, as typified by the Lapack project at the University of Tennessee and other cooperating places. Nor is there much pressure to develop standardized software; vendors and users still develop libraries and user interfaces for their own platforms and applications. Japanese computer users can and do write their own application software. People who have studied it from the inside claim it can be quite good.

Questions regarding this column can be addressed via e-mail to David K. Kahaner, US Office of Naval Research, Far East, at kahaner@cs.titech.ac.jp.

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## Micro Standards

# "Fair is foul, and foul is fair"

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Everyone seems to believe in open systems, but curiously no one seems to agree on what they are. Claims of "openness" are everywhere, and are nowhere more prevalent than in the advertisements of many computer hardware and software companies. One software vendor proclaims that its operating system product is "open," presumably because anyone can openly buy it at a local software store. A hardware vendor claims openness because its proprietary computer is based on a microprocessor chip that anyone can buy. Another hardware vendor claims that a proprietary computer architecture is "open" because it runs a proprietary operating system available from several other hardware companies, which make the same assertion. Nearly all users and many vendors are tired of these self-serving claims.

More importantly, how does the IEEE standards development program relate to such claims of openness? Let me use an older analogy to relate the standards activities of the IEEE to the current outbreak of "openness." A classic recipe with which many people are familiar is the famous scene from Macbeth (Act IV, Scene i), in which the witches chant:

> Double, double toil and trouble;
> Fire, burn; and, cauldron, bubble.
> Fillet of fenny snake,
> In the cauldron, boil and bake;
> Eye of newt, and toe of frog,
> Wool of bat, and tongue of dog.

Frequently when whipping up the souffle of openness, the same sort of recipe will be used, with a dollop of standards thrown in. This witches' brew of product attributes then produces something like "industry standards," which can—and usually does—mean just about anything. As with many vague recipes, the resulting product is usually unreproducible, since the original rules for creation didn't specify how hot the cauldron was supposed to be (bubbling temperature?), how big the fenny snake fillet (the 6- or 12-ounce variety), nor what type of dog to use.

Contrast this with the recipe for a formal standard. The rules are simple since ANSI requires that all American National Standards be developed using rules that mandate openness, fairness, and equity. Proper rules—ones that all participants help to determine—require precise definitions and specify exact amounts. Requirements are agreed upon in a public forum, and constant review makes sure that the recipe is publicly available and capable of being duplicated. The result is an accepted agreement on a way to "do something"—whether it is to create a local area network (IEEE Std. 802) or a RISC (reduced instruction-set computer) architecture (IEEE P1754). These recipes are published, not in Shakespeare nor the fiction section of a library, but in books with the title of *American National Standards* or *International Standards.* And these books are available for sale and for use in implementing a product based upon the interface specified in the standard. The standards process has been around for a long time. So why is there a sudden need to embrace "openness" and the invention of all of the types of new open recipes? Simply put, open systems are hot today because customers want them.

Open systems offer users better value and safety, allowing customers to protect their investment in the face of the increasing globalization and specialization of the information technology industry. Users of open systems are less subject to unpleasant surprises in price, performance, or

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availability, at the whim of a vendor. Because today's users are decentralizing and distributing their applications across heterogeneous networks, the number of distributed applications is increasing dramatically. Such a world is greatly facilitated by truly open systems.

Another option, of course, is to make a single vendor the answer to all of your computing needs, which works equally well for ensuring interoperability. However, if that vendor falls behind the technology or price-performance curves, or stops producing a particular solution, your computer environment becomes obsolete. That's why open systems usually are expected to be multivendor systems.

If open systems are multivendor systems, how do these vendors agree on the way their systems are to interface with each other? If one company (or group of companies) creates or maintains the definition of the interface, it could have a permanent advantage in time and performance over any others who use the interface. Because such a specification is not defined through an open process, it is a proprietary specification, even if implemented by multiple vendors. The first requirement for open systems, then, is that they be based on open standards; open standards are standards developed with an open, consensus-based process, as are all IEEE standards. To paraphrase Woodrow Wilson, open systems require "open standards, openly arrived at."

## Interface v. implementation

Interface standards, as opposed to implementation standards, are the second requirement for open systems. An interface is like a set of acceptable building practices for a house. Building practices tell generally how houses should be built, and what kinds of materials should be used for a particular purpose. When an architect designs a house, implementation-specific decisions are made about how many floors the house will have and how many bedrooms are to be built; each decision ultimately will choose either to implement or not to implement building practices. An implementation standard is a plan for a particular house—every house built to an implementation standard would look the same, allowing minimal innovation.

Note that I am not talking about the building codes, which are local and county regulations. These regulatory standards cover things such as safety and sanitation; you must plan to follow them or the county will not issue a building permit. Rather, I am discussing interface standards that make recommendations (36-inch exterior door, 30-inch counter height, 1/2-inch copper plastic pipe). This sort of interface standard facilitates innovation: Walk around and see how many different designs (implementations) can be built that implement the same interface (building practices). Because these are interface standards, and because multiple vendors implement these standards, the average home buyer has a wide choice of standard-size doors, each of which is or can be individualized. If the buyer wants a nonstandard implementation, it can be designed, but the interface may be violated. There will be an associated cost with this variation, including challenges with trying to move appliances (which are built to fit through standardized doors).

## Unobstructed access

The third requirement for open systems is that use of the interfaces be free of unreasonable legal, financial, or other restrictions. I mentioned earlier that competition is a critical factor in open systems; real competition isn't practical without free access to the interfaces. Even apparently moderate royalties or innocuous-seeming administrative requirements can stifle competition, to the point that the interface isn't truly open. To use the building example, if there were a $100 fee per door charged to the manufacturers of 36-inch exterior steel doors (for use of the interface called the "36-inch door interface"), the use of the 36-inch door would be very limited. It would be economically unworkable. Similarly, interfaces that allow implementations in the information technology industry must be open—something that is guaranteed by an American National Standard, but not guaranteed by an "industry standard," which is usually a de facto marketing-based activity.

## Quality standards

Quality standards are the fourth requirement. In this context, quality refers to the attributes of the interface standard—the interface must be characterized by adequate (though not necessarily maximum) performance, completeness, lack of ambiguity, and conciseness. While meeting these requirements is possible, it requires knowledge and hard work. See my column in last December's issue of *IEEE Micro* for a discussion of quality standards.

The title of this column is taken from the opening scene in Macbeth, in which the three witches gather to make their baneful brew that signals the doom of Macbeth. It is the situation in which the industry now finds itself—fair does seem foul (formal standards are too slow, too complicated and awkward, too rule bound). At the same time, claims for industry standards have become all the rage—but more and more they are proving to be major sources of confusion. Over time, and probably after a certain amount of tragedy, good will triumph, and the benefits of truly open systems and standards will become available to both users and vendors.

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Micro Law

# A guardedly cheerful note—for a change


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Over the last year, things have begun to look up a little in copyright law. (I put aside the recent law for "felonizing" certain software professionals, an issue discussed elsewhere in IEEE publications.) In a series of decisions by appellate courts in various parts of the United States, a trend appears to be emerging against "lookie-feelie" and legal metaphysics treatment of copyrights in computer programs. Courts are beginning to substitute common sense for the mumbo jumbo of "sequence, structure, and organization" and "nonliteral aspects" of computer programs.

## The past was prolog

A year or two ago, and through most of the 1980s, the trend of court decisions was that computer programs and their copyrights emanated some ineffable miasma that defied any explicit description. But if competitors came too close to whatever it was in developing a competitive software product, they would be held guilty of copyright infringement and heavily mulcted for their insolence. Underfunded software start-up companies were unable to withstand litigation assaults based on these legal doctrines, and repeatedly were compelled to withdraw from the market when sued, or threatened with suit, by established software marketers. Stemming largely from the decision in *Whelan Associates, Inc.* v. *Jaslow Dental Laboratory, Inc.* in 1987, this trend of decision led to suits against competitors based on their copying such expressive elements of plaintiffs' computer programs as the following:

- placing screen captions at the top center of the screen;
- using the color blue as screen background;
- designating which keystrokes a user should press to enter the program function that a given screen menu word designated, by capitalizing and highlighting (making brighter) the letters of the menu word corresponding to the keystrokes;
- labeling the opening menu of a program as "Opening Menu;"
- using pull-down menu windows in reverse video;
- using the same command language to operate program functions;
- using the same commands and keystrokes for given program functions that the plaintiff's earlier program used for those functions;
- having the same list of commands and tasks to be performed;
- using the same switch patterns on a machine's front panel to actuate the machine's software; and
- imitating the plaintiff CADAM's computer program by being "too CADAMish."

In this last item, CADAM, a major CAD/CAM software developer, sued start-ups Adra and Adage for marketing computer programs that copied the "look and feel" of the CADAM program. In addition to charging the defendants with marketing and promoting a "CADAMish" program, the plaintiff complained of the defendants' marketing their program as "CADAM-compatible" and "a CADAM look-alike." (See *IEEE Micro,* Apr. 1986, pp. 64-65.) The defendants apparently exited the market rather than bear the expense of resisting the copyright infringement action.

Mesmerized by analogies that ingenious counsel drew between computer programs and poems, novels, and plays, some courts resolved to protect what they imagined to be the "plot,"

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"style," and "characterization" of computer programs. They anomalously treated copyrights on computer programs as if they were patents.

(The leading US precedent against doing so is *Baker* v. *Selden* in 1879. As the Supreme Court explained in that decision, treating a copyright as if it were a patent defrauds the public, because a patent monopoly is foisted on the public without the built-in protections of the patent system.)

The courts drew the line between unprotected *idea* and protected *expression* at such a high level of abstraction that virtually any competing computer program would be found to have taken *expression* and thus have infringed the copyright. At the same time, they consciously elevated the legal metaphysics of copyright law above the parties' mere "commercial and competitive objectives."

Many of those in the software industry (and probably the overwhelming majority of working software professionals) became convinced that courts were incapable of resolving software rights disputes sensibly. They felt this way because the courts' legal tools were inadequate to the task and because the judges (coming from the wrong one of C.P. Snow's two cultures) could not understand software. As one court recently observed, responsive proposals were to substitute a *sui generis* (unique) software law or "industrial copyright" type of industrial property law for the present law of software copyrights, and to establish an expert software tribunal in place of courts.

Things seemed to have reached a new low point by early 1992. One district court in Massachusetts simply dismissed out of hand the legal relevance of problems in having to learn new and unfamiliar computer program user interfaces (*Lotus Development Corp.* v. *Paperback Software Int'l*) and another district court in San Francisco found disassembly of code unlawful per se (automatically) under the copyright laws (*Sega Enterprises, Ltd.* v. *Accolade, Inc.*, later reversed on appeal).

## What's new

Very recently, however, a seemingly contrary judicial consensus has emerged. Quite suddenly, a majority of US courts have rejected the *Whelan* rationale and have said that a copyright on a computer program is *not* a patent, and must be interpreted more modestly. Recognizing the flawed logic of *Whelan* and its progeny, the US Court of Appeals for the Second Circuit (New York) pithily summed up the current thinking in *Computer Associates International, Inc.* v. *Altai, Inc.*, 1992:

> Rightly, the district court found *Whelan*'s rationale suspect because it is so closely tied to what can now be seen with the passage of time as the opinion's somewhat outdated appreciation of computer science. *Whelan*'s approach relies too heavily on metaphysical distinctions and does not place enough emphasis on practical considerations.

Under recent decisions —the Second Circuit's decision in *Altai*, and the Ninth Circuit (San Francisco) decision in *Brown Bag Software* v. *Symantec Corp.*, 1992—a new method of legal analysis for software copyrights has emerged. First, the court filters out all unprotected subject matter (elements dictated by efficiency or external factors, and public domain subject matter) to derive the copyright owner's protected residuum (what is left after subtracting the unprotected subject matter). The court then compares the residuum with the accused work of the defendant. Only if what the defendant took from that residuum (disregarding the rest) was substantial is the defendant is an infringer.

These decisions also recognize the appropriateness of trial courts having their own expert software witnesses assist them in addressing the intricacies of programming's technical issues. Other recent decisions—*Sega Enterprises Ltd.* v. *Accolade, Inc.* in the Ninth Circuit and *Atari Games Corp.* v. *Nintendo of America, Inc.*—establish the legitimacy of disassembly and reverse engineering of computer programs when necessary for legitimate commercial objectives. Somehow, something suddenly became different.

## Now what?

Is everything in computer software copyright law now wonderful? Is there no longer any need to fix the system, since at the moment it does not appear to be broken?

Unfortunately, the system may still be badly bent, even if it is not completely broken. The structural problems that led to the many complaints by software professionals and others in the industry remain. That the courts are beginning to learn how to be more rational in applying copyright principles to computer software does not mean that copyright law is a legal scalpel, after all, rather than a blunt instrument. Both the Second Circuit in *Altai* and the Ninth Circuit in *Accolade* warned against "forcing a square peg into a round hole." They meant that when one tries to apply ordinary principles of copyright law to computer software, one gets very peculiar results—sometimes quite startling or bad ones.

Unless we devise a round peg for a round hole (or square off the hole, if you prefer), we shall continue to lurch from one software law crisis to another. That the present crisis seems to have passed is no proper cause for self-congratulation. Future software crises must be anticipated until the structure of software law is mended.

The European Community's *sui generis* database directive, the 1984 US *sui generis* chip topography law (emulated by chip topography laws of many other nations), the Japanese *sui generis* software law proposals of the early

1980s, the WIPO (UN World Intellectual Property Organization) *sui generis* software proposal of the late 1970s, and (catch this) IBM's *sui generis* software proposals around 1970 have all pointed to the right way. We need a properly thought-out *sui generis* utility-model type of law for computer software. It should treat software (at least in its noncode, nonliteral aspects) as the industrial property that it is, not as a species of poem or oil painting. Bridging the two cultures may be a noble idea, but the software industry would experience much less wear and tear if the experiment were carried out at some other experimental subject's expense.

That is not to say that we need software patents as the solution. The three decades of the Algorithm War in the US have shown that patents do not work properly, either, for abstract aspects of software. We need a system that borrows appropriately from copyright law, patent law, utility-model law, and perhaps European imitation law as well. It should combine selected features of each, and new features where the nature of software dictates it, to provide a form of legal protection that properly fits the subject matter to the commercial needs of industry, software professionals, and software users, and to the interests of the public. The task of crafting such a system is not easy or fast, but the alternative is perennial ineptitude and recurrent crisis.

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# Software Report

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## Malaysia and Singapore

Malaysia confounded my expectations on my first visit there. From my readings, I had expected to find a Third World country, agriculture driven and visibly regulated by a strong Islamic fundamentalism. Not so, at least from what I could see.

Kuala Lumpur, the capital, looks strikingly like its southern neighbor, Singapore, must have looked only a few years ago. Large residential, commercial, and hotel construction abounds. Ultramodern skyscrapers jostle for space with ancient mosques. Many of the structures are weary, true, but many new department stores and slick malls have gone up as well. Coming soon to a downtown site being vacated by a racetrack is the tallest building in Southeast Asia, over 90 stories tall. A telecommunications tower, being built jointly with the Germans for $100 million, will be over 420 meters high, the world's third tallest tower and Southeast Asia's highest.

Pedestrians and vehicles throng the city's streets and shops: Unlike Singapore, Kuala Lampur has no subway system, so buses are packed. Though many Malaysian women still cover their faces with traditional black Moslem garments, many more wear brightly colored clothing. Western jeans, pants, and tee shirts are everywhere. Stores overflow with the usual cornucopia of Japanese electronics, plus clothing from famous houses around the world. The fashion conscious, sipping their cappuccino and Perrier, crowd the city's cafes.

The road between the capital and the airport (about 30 km) is lined with multinational factories. According to my taxi driver, the downtown Hilton is busy, but not nearly so as the one near the airport, a more convenient stop for international business people visiting their Malaysian subsidiaries. A new international airport, Southeast Asia's largest, will be built about 40 km from the capital at an estimated cost of $8 billion; the old airport will service domestic flights. The road south from Kuala Lumpur toward Singapore is new, multilaned, and spacious, though not completed all the way to the border. The countryside shows substantial evidence of new building, along with plenty of examples of agriculture, primarily rubber and coconut palm plantations. The government has earmarked about $40 billion for infrastructure, social development, and defense expenditure over the next five years. In most areas of economic development Malaysia leads Thailand, and per capita income is almost twice as high.

Malaysia, formerly British-ruled Malaya, gained its independence in 1957, and now is ruled by a constitutional monarch elected on a rotating five-year term basis by the nine hereditary sultans of the traditional Malay states from among themselves. The country occupies the southern half of the Malay Peninsula, which connects through Thailand to mainland Asia, and about half the large island of Borneo to the east. Malaysia has almost 18 million people of whom about 30 percent are of Chinese

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extraction, 9 percent from India or Ceylon (mostly Hindus), and most of the others Malay; almost all the latter are Moslems.

Large and not heavily populated by regional standards, Malaysia is well endowed with natural resources, including lumber, oil, and natural gas. Previously, the British focused on tin and rubber as well as shipping; tin exports now run at a rate of about $300 million, about one fifth the amount obtained from palm oil. The city of Malacca (150 km south of Kuala Lumpur) on the mainland's west coast was Portuguese, then Dutch, then British, and is at the juncture of trade routes between Europe and the Middle East. The adjacent Straits of Malacca are still among the world's busiest waterways.

Recent growth has been very strong, averaging about 8 percent annually since 1980. Unemployment is just over 4 percent, considered full employment, but a shortfall of more than half a million workers is predicted by the end of the decade. Rapid growth has generated a modest amount of inflation (around 4 percent), and the country has a weak balance-of-payments position, the latter fueled by increases in consumer spending and foreign investment. The manufacturing sector claims that its labor pool is already short by 80,000 workers. Many foreign workers, including more than half a million from Indonesia, are employed illegally. At the same time, higher salaries and opportunities elsewhere are attracting skilled Malaysians to move out of the country, a situation Korea, Taiwan, Hong Kong, and other rapidly developing countries in the region have also faced. However, many of these Malaysians are returning to their homeland in senior positions, now that the economic outlook is brighter.

Many Western companies have found a home in Malaysia, and investment from outside Malaysia is very strong, more than $6.5 billion in 1990, with France and Australia involved in two large refinery projects. Taiwan has been Malaysia's largest investor, with almost $5 billion since 1987, though the rate has been reduced recently, as Taiwan has shifted its attention to mainland China and because a $3 billion steel plant project is still on hold. While I was there, Motorola celebrated its 20th anniversary in Malaysia, having invested more than $350 million, and its Malaysian subsidiary has been given the task of spearheading the entry into China. Motorola records substantially more than $1 billion in turnover at four manufacturing facilities here, between 20 and 30 percent of the company's global output.

If current plans are implemented, Malaysia will spend a great deal of money developing its research and development base. By the turn of the century, the country plans to spend 2 percent of its GDP on R&D expenses (1.5 percent by 1995). Most of this increase should come from the private sector whose contribution is predicted to increase to about 60 percent of total expenditures. Five priority sectors have been identified: biotechnology, automatic manufacturing, advanced materials, electronics, and information processing. The current budget allocates about $250 million to strengthen existing R&D institutions and promote joint research between private, university, and government institutes.

## SEARCC 92

The 11th annual South East Asia Regional Computer Conference, held this year in Kuala Lampur, was attended by about 650 delegates. Composed of computer professionals from Pakistan, India, Sri Lanka, Thailand, Malaysia, Singapore, Indonesia, Hong Kong, Philippines, Australia, and New Zealand, SEARCC is designed so that information technology (IT) professionals can meet and share information. SEARCC is not primarily a research conference on computer science, although some research activities are featured. This year's conference theme was "IT: Building Information Infrastructure for National/ Regional Growth."

At the conference, we learned that Malaysia has officially embraced open systems for public sector procurements, meaning that government agencies that are planning to purchase computer systems, software, and so forth, can specify their requirements in terms of various IEEE, ANSI, and ISO standards for general principles, operating system interfaces, programming languages, commands, utilities, networks, device interfaces, data management, interchange and compression, databases, user interfaces, and security and system development methodology. They can then expect that vendors will be able to comply on the basis of satisfying the standards detailed in these documents. At the moment, agency participation is voluntary. Nevertheless, this is really quite a different situation from say, Japan, where open systems have not been as healthy as their proponents would like.

The conference included much discussion of the status of software versus hardware in Southeast Asia. Most emphatic on this topic was Stan Shih, founder and chair of Acer, Taiwan's largest computer company (more than $1 billion in sales in 1991), and the most respected Asian computer maker outside Japan. Shih recommends moving away from hardware and into software. For the past 10 years developing Asian countries have concentrated heavily on the development of PC-related hardware; this part of the world is now one of the world's leading PC hardware manufacturing centers. But intense competition among PC hardware manufacturers will reduce profit margins, and the future lies in the development of value-added software, primarily in an open system environment. Shih detailed specific steps:

- Develop highly focused and niche products initially, such as firmware bundled products, concentrating on the regional markets in Asia and use PC marketing channels already operational for exporting software.
- Cultivate software experts by training more people. Enlist government support in training personnel

- from academic or industrial sources in the development of highly specialized products. Establish software development centers in countries with existing software manpower.
- Attract well-known software houses for local investment by offering incentives. Transferring development technology from these companies would push software produced in Asia forward to world-class standards sooner than by producing software independently.

"Most important," he says, "is the formulation of long-term development strategies, creative and customer-driven marketing, product quality improvement, strong product support, and continuous product research and development that will make a world-class competitor." In my opinion, this kind of philosophy has no relation to what one normally associates with Asian software; if implemented, watch out Microsoft!

### Exhibits

More than 50 organizations were represented at the heavily attended exposition that accompanied SEARCC 92. These were mostly vendors demonstrating open system applications and PC/WS commercial hardware products. The PC clone business is slow, and several vendors were offering "fire-sale" prices for 386 and 486 systems, even throwing in computer tables or other encouragements.

One particularly interesting exhibit involved the work at the Center of the International Cooperation for Computerization. CICC, a nonprofit organization founded about 10 years ago by the Ministry of International Trade and Industry (MITI) of Japan, is designed to implement cooperative activities that promote computerization in developing countries. More than 50 Japanese companies participate, and there are activities in almost 20 countries.

CICC's main cooperative research activity is a machine translation system for Asian languages (currently Chinese, Thai, Indonesian, Malaysian, and Japanese), work that has been in progress since 1987 and will run through 1993. In Japan it involves researchers at the Electrotechnical Laboratory (ETL), CICC's Machine Translation System Laboratory, the Japan Electronic Dictionary Research Institute, and various computer manufacturers and software houses. Each of the four other countries also has a research institute associated with the project. CICC has contributed over $3 million toward the project. The main approach is to pre-edit text to make it easier to translate, followed by morphological, syntactic, and semantic analysis, and eventually conversion into interlingua using the rules of sentence analysis grammar. In other words, an intermediate language is used as the pivot for translation, after which sentences are generated in the target language. Main applications are to translate technical documents at high speed.

### Singapore as role model

Meanwhile, Malaysia is trying to copy those aspects of Singapore's development that seem appropriate. No doubt, little Singapore has been a tremendous success, and is an inspiration to it neighbors. Even during the current recession its economy has expanded at a real rate of 5 percent during the first half of 1992, and unemployment is 2 percent. Inflation since 1974 has averaged less than 4 percent (US average during this same period was about 6.5 percent), and this year it should be roughly 2.5 percent, about one third of the average wage increase. Singapore's 1991 per capita GDP was $20,400, compared to $14,900 in 1984 (this corresponds to a GNP of $13,271 in 1991). The future also looks very bright. Economists have predicted that Singapore is very likely to be among the 20 richest countries in the 21st century. To do that it has to continue to focus on people and seven major industries: microelectronics, biotechnology, new materials, civilian aviation, telecommunications, robots and machine tools, and computers and software. Success will come if other countries in the area allow Singapore to become the headquarters city for the region, while they are also moderately successful themselves.

Singapore's government has a very definite slant to economic development. "It is Singapore versus other countries," says Singapore's Prime Minister Chok Tong Goh as he places Singapore's team approach squarely between Hong Kong's every man for himself and New Zealand's state welfare approach. (Goh singles out New Zealand as a case of what not to do; a country that was fifth richest in 1966 and is now 19th, while Singapore has gone from 33rd to 18th during that same period. Goh's explanation: New Zealand's ranking fell because its welfare subsidies increased the dependency of the people and sapped their competitive drive.) According to Goh, the key is giving people incentives to strive: good pay and light taxes. (Singapore's beginning tax rate is 3 percent, compared to 15 percent and 30 percent in Japan and Sweden; half of Singapore's taxpayers, about 500,000, pay $100 or less in taxes.)

Goh also wants to make Singaporeans asset owning. Currently, only 14 percent of adults own shares in publicly listed companies (compared with 21 percent in the UK and 27 percent in Japan), and Goh hopes to increase that to 30 percent. The government plans to sell shares in Singapore Telecom at a discount next year, and also plans to sell shares in the Mass Rapid Transit, Port of Singapore, and a new company formed to run the country's electricity and gas departments.

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# Micro Review

## Good books and good software


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I look at many books and software packages in the course of preparing this column. I select items for review that I think you will find interesting or important in your work. I also try to select products that are worth your trouble and expense in obtaining and using them. In other words, I like to choose products that I can recommend enthusiastically. Negative reviews have an important role to play in other contexts, but I think that positive reviews are more useful here.

Since there are so many more good products than I can provide in-depth reviews of, I've decided to give you a potpourri of short reviews this month. Please let me know if you find this approach useful. If so, I'll do it again from time to time.

### Books

***Debugging—Creative Techniques and Tools for Software Repair***, Martin Stitt (Wiley, New York, 1992, 432 pp.; $32.95)

This book is a gold mine. It deals almost exclusively with assembly-level debugging, principally for the Intel 80x86 architecture running the MS-DOS operating system. What Stitt says within that framework comes from his obviously deep understanding of more general principles.

Stitt wants to teach you how to approach software performance anomalies. He wants you to forget stereotypes about "the black art of debugging." He wants you to adopt a disciplined, systematic approach to problems. This approach requires you to diagnose with cool detachment, attend carefully to detail, and never lose sight of the forest for the trees. Debugging may not be your favorite activity, but as Stitt points out, the better you are at it, the less time you'll have to spend doing it.

I've seen many books that attempt to teach disciplined, systematic approaches to software tasks, and most of them aren't worth the paper they're printed on. This one is different. Stitt demonstrates in his writing the same detatched analysis, attention to detail, and broad view that he wants you to adopt in debugging.

I've been programming computers since 1960. I've always enjoyed and had great success at debugging my own programs and those of others. This is the first decent account I've seen of the problems and techniques of debugging. I began my evaluation of this book by opening it at random to about a dozen different places and reading a paragraph or so at each place. Each time my reaction was "yes, yes, yes." Assembly-level debugging may not appeal to you, but if you do any programming at all, you can probably benefit from this book.

***Inside Windows NT***, Helen Custer (Microsoft Press, Redmond, Wash., 1992, 416 pp.; $24.95)

David Cutler, who led the designs of Digital Equipment Corp.'s RSX-11M and VMS operating systems, came to Microsoft in October 1988 to lead the development of their next-generation operating system. Windows NT is the result. When it's finally ready—probably some time this year—it will take its place at the high end of the Microsoft line, providing upward compatiblity for DOS and Windows applications.

Helen Custer spent three years as part of the Windows NT design team. Her job was to write this book. Before starting, she read Tracy Kidder's *The Soul of a New Machine* for inspiration, but her book is not meant to be anything like Kidder's. Custer's book focuses more on the structure of the final product than on the human and intellectual story of its creation. She mentions



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the names of members of the design team and gives them credit for their specific contributions, but that's as far as she goes with the human element.

Custer starts from market needs and design goals, gives an overview of the resulting design, then spends the rest of the book giving an in-depth view of the operating system components. Depending on how much you care about such things, you will find this material somewhere between deadly dull and intensely interesting. Wherever you fall on that spectrum, you'll probably appreciate Custer's clear writing style and the book's open format. Custer has written an accessible account of an important new system.

If you want to understand Windows NT, this is the authoritative account. It will probably be the best book on the subject for a long time to come.

***The Elements of Friendly Software Design—The New Edition***, Paul Heckel (Sybex, Alameda, Calif., 1991, 349 pp.; $22.95)

The original edition of this book appeared in 1984. The new edition contains the original edition as an unmodified subset. The new material tells the story of Heckel's battle to assert his patent rights against the giants of the computer industry, particularly IBM. Heckel presents his side persuasively and generalizes to the problems faced by all inventors, but it is still only his side of the story. I found it fascinating, but it is of much less general interest and importance than the original material.

Paul Heckel is an original thinker. His fundamental message is that software design is a form of communication. This metaphor allows him to draw immediate parallels between software design and other forms of communication, notably film. This thought process leads him to 30 maxims, which he expands upon with examples from software design situations and from everyday life.

Heckel tells us that we have to overcome our instincts before we can design friendly software. These counterproductive instincts are:

We think logically, not visually.
We base our designs on our knowledge, not the user's.
Our programs evaluate our user's actions.
We make our programs take control.
We think in generalities, not specifics.
We structure for internal organization.
We strive for a program's internal simplicity.
Our knowledge constrains our vision.

In a newly added chapter written with Chuck Clanton, Heckel says that the most critical aspect of user interface design is the design of conceptual models. These facilitate communication between the designer and the user and form a framework that the user can become comfortable in. The most helpful conceptual designs are metaphors, that is, analogies with real-world situations. These allow the user to bring existing skills and knowledge into the new situation.

Heckel moves from theorizing about metaphors into describing his own card-and-rack metaphor. He compares and contrasts it with the well-known desktop and spreadsheet metaphors. This is interesting material, but ties again into his patent problems.

At one point Heckel quotes Blaise Pascal, "Anything that is written to please the author is worthless." I hope Heckel will take that message to heart and will someday bring out a version of the book that finds a better way to communicate the lessons of his recent problems. Very little in this fine book can be considered worthless. But there is a distinct difference in perspective between the parts that teach friendly software design and the parts that document and support his business struggles.

Until that new version comes out, you should buy this one. It's still the best book on user interface design.

***μC/OS—The Real-Time Kernel,*** Jean J. Labrosse (R&D Publications, Lawrence, Kansas, 1992, 284 pp.; $29.95)

This is an extremely instructive book. It's not a polished job of publishing, and the text could use professional editing, but the subject redeems all of that.

Real-time kernels are important in embedded systems, but few books have been written about them. Companies like Ready Systems and Wind River have developed excellent products in this area, but they are not in a hurry to give away their secrets.

Labrosse understands the requirements, many of them counterintuitive, of real-time systems. He has written a real-time kernel in C with a small amount of carefully isolated assembly language. His book is essentially an annotated listing of that kernel. A separately available diskette contains the entire source code.

Obviously, this kind of book is not for everyone. For the person who works with embedded systems, this book is worth looking for.

## Software

**Microsoft Word 5.1 for the Macintosh and Word for Windows 2.0** (Microsoft Corp, Redmond, Wash.)

I've been using Microsoft Word for the Macintosh for a long time—on my original Macintosh, on its successor the Mac Plus, and on my current SE/30. It's a powerful, full-featured word processor, and I like it very much. Until now, it has always been better than the corresponding product for the PC. Now, however, Word for Windows is at least as good as Word for the Macintosh. In some ways it's much better.

Of course, there are the differences in the platforms. My Macintosh SE/30 has a tiny black-and-white screen, while my PC has a super VGA color display of more than twice the area. My SE/30 has a 16-MHz 68030 processor, a 40-Mbyte hard disk, and 4 of its 8 Mbytes

of memory are sitting in a drawer, waiting to be reinstalled. My PC has a 33-MHz 80486, a 200-Mbyte hard disk, and 16 Mbytes of main memory.

It's depressing to have less than 60 percent of my screen available for text when I run Word 5.1 for the Macintosh. It's depressing when my screen saver runs a banner across the top of my screen saying that it doesn't have enough memory to run. But beyond these psychological effects, Word for Windows excels Word for the Macintosh in its conceptual model.

The features of Word for Windows are organized around styles, document templates, fields, and the Word Basic macro language. Word for the Macintosh has no macro facility and uses ad hoc approaches to indexing and other applications of fields. It seems to be evolving toward document templates. Both versions handle styles similarly.

The Windows operating system has an object linking and embedding (OLE) feature, which allows dynamic linkage between files. Apple's System 7 operating system for the Macintosh has a similar capability. Word for Windows seems to make better use of this kind of file linking than Word for the Macintosh does.

Word will probably remain my word processor of choice in the future, but I may take the plunge and move from the Macintosh to Word for Windows.

**MKS Toolkit 4.1 for DOS** (Mortice Kern Systems, Waterloo, Ontario, Canada; US$299)

If you're used to Unix and you have to use DOS, this package can give you all the comforts of home. The package contains a complete implementation of the Korn Shell, uucp, the vi editor, an excellent implementation of awk, a make facility, pipes, tar, and all of the most popular Unix utilities. All told, the package gives you a 3-inch stack of manuals and about 6 Mbytes of programs, examples, and on-line tutorials and documentation.

The relatively painless installation procedure also sets up a rudimentary Windows interface to some of the tools. This looks nice but doesn't really add much to the basic tool set, since Unix tools are all essentially optimized for use from the command line.

This package is designed for programmers, but anyone familiar with the Unix environment will appreciate it immediately. If you use DOS and you don't know much about Unix, this is a good way to find out what all the fuss is about. Be careful—you might not be able to go back to DOS.

**Speed Reader Windows Version** (Davidson & Associates, Torrance, Calif.; $49.95)

This is a straightforward training package to improve your reading skills. There are no gimmicks. The authors have incorporated well-known principles of reading into a neat package. They have integrated the package competently, if not elegantly, into the Windows environment.

There are six basic activities: warm-ups, eye movement, newspaper reading, paced reading, timed reading, and the Eye Max peripheral vision exercise. The program lets you log in by name and keeps track of your progress on the various activities. You can examine a log of your sessions or look at bar graphs of your progress. The package keeps track of your reading speed and comprehension level for each type of activity.

If you've ever played computer games and watched your scores rise as your competence improved, here's a chance to try the same process to develop a useful skill.

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Microelectronic Systems Branch at Goddard. "The silicon alternatives we evaluated were either too slow or consumed too much power," he added.

The GaAs chip forms part of the second Tracking and Data Relay Satellite ground station upgrade at White Sands, New Mexico, and could support the future deployment of Space Station Freedom and the Earth Observing System. It features a programmable search, check, and lock strategy for synchronization of data frames up to 32 Kbits in length and provides double-buffering of output data. Standard microprocessor control logic using standard TTL control signals controls the device.

Vitesse Semiconductor Corporation headquarters in Camarillo, California.

## Editorial Board changes

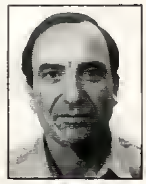
Editor-in-Chief Dante Del Corso announces several changes in *IEEE Micro*'s Editorial Board. Board member Maurice Yunik will join K.E. Grosspietch and Ashis Khan as Associate Editors in Chief. Yunik, of the University of Manitoba, will support Del Corso in seeking and reviewing manuscripts from US and Canadian authors.

Del Corso also welcomed three new Board members: Stephen L. Diamond, Osamu Tomisawa, and Uri Weiser.

Diamond is director of standards at SunSoft, Inc., in Mountain View, California. He is chair of the IEEE Microprocessor Standards Committee, Policies and Procedures, chair of the Computer Society Standards Activities Board, and a member of the US delegation to ISO/IEC JTC1 SC 26, the Posix Executive Committee, and the X/Open and Sparc International boards and committees. He will reprise the magazine's Micro Standards column (see p. 71 this issue).

Tomisawa and Weiser will speed the review of manuscripts for *Micro*.

Tomisawa manages the Microcomputer Department B at the Kita-Itami Works of Mitsubishi Electric Corporation, where he works on memory and logic VLSI design. He is a member of the IEEE and the Institute of Electronics, Information, and Communication Engineers of Japan, and an associate editor of *IEICE Transactions on Electronics.*



Weiser is Microprocessor Group manager, Platform Architecture Center, Microprocessor Architecture Development for, Intel Israel in Haifa. He has served as chair and a member of the Program Committee for a variety of conferences and symposiums including ICCD, Computer Architecture, Hot Chips IV, and CompEuro.

## Micro bits

• Vitesse Semiconductor is sponsoring a **design contest** that illustrates the use of the Viper GaAs gate array. Entries must be postmarked by March 31, 1993; prizes will be awarded. If interested, call Vitesse Marketing at (805) 388-7455.

• Striving for a tenfold increase in **semiconductor manufacturing productivity** is Texas Instruments' Microelectronics Manufacturing Science and Technology project. Funded by DARPA and USAF Wright Laboratories, MMST uses object-oriented programming and database technology and "revolutionary concepts."

• **TI and IDT** signed an alternate source agreement for logic devices with built-in boundary scan. Each will offer advanced bus interface and LSI controllers that comply with the JTAG/IEEE 1149.1-1990 testability specifications.

• **Wireless LANs** may capture 17 percent of all LAN shipments by 1997, according to BIS Strategic Decisions, Norwell, Mass. The reason: improved economics from wired networks, standards activity, and the emergence of more mobile computing devices.

• The Dataquest market research firm lists Motorola as the leading worldwide supplier of **8-bit microcontrollers**, ranking the 68HC05 and 68HC11 first and ninth in worldwide shipments.

## Literature

Technology trends, key issues, opportunities, and market growth rates form the major part of this study on the RISC market. *"RISC Impact on the Computer and Workstation Markets," Electronic Trend Publications, Saratoga, CA; (800) 726-6858, ext. 1091; $495.*

Database programers at any level who plan to develop applications for the Clipper 5.0 should benefit from this 1,351-page book by Joseph D. Booth. It includes an introduction to the basics and advanced networking, debugging, and pop-up programming information. *Clipper 5: A Developer's Guide, M&T Books, San Mateo, CA; (800) 688-3987; $44.95, book and disk.*

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# Micro News

*Send information for inclusions in Micro News one month before cover date to Managing Editor,* IEEE Micro, *PO Box 3014, Los Alamitos, CA 90720-1264.*

## ISO's smart highway TC

Noting the significant US and overall international community interest, the International Organization for Standardization Technical Board established a new technical committee for intelligent vehicle/highway systems, which it calls Road Transport Informatics. The TC's scope will include standardization in the field of smart highways, Advanced Traveler Information Services, Advanced Traffic Management Systems, Advanced Vehicle Control Systems, Advanced Public Transportation Systems, and Commercial Vehicle Operation. Pending approval by the ISO council, the Technical Board decided to allocate the secretariat for this committee to the US through the American National Standards Institute.

Standardization work for smart highways is also taking place in the European CEN, CENELEC, and ETSI committees; in addition, the International Electrotechnical Commission proposes to establish a new technical committee for road traffic signal systems.

For further information contact ANSI at 11 West 42nd Street, New York, NY 10036.

## US to participate in Japan's Real World Computing program

The US and Japanese governments plan a joint prototyping project to further the design and development of advanced computing technologies that combine light-wave and electronic components. The hybird systems to be worked on would serve as a bridge between today's electronic computers and the fully optical, parallel processing machines envisioned for the future.

Part of Japan's 10-year, $500-million Real World Computing program for information processing, the new optoelectonics project will involve researchers and processing facilities in both nations. A 10-member joint management committee with five representatives from each country will guide the project; Judson French, National Institute of Standards and Technology, will chair the US group. Plans call for establishing a service that links designers of optoelectronic devices and modules with production facilities, or "foundries," through a broker. Each country will select its own broker and arrange the funding for its participants. Japan's MITI will finance the broker in both the US and Japan.

Although the collaboration forms only a small component of the overall RWC program, it allows both countries to develop a model for cooperative research that could lead to other cooperative projects.

For more information, contact the White House Office of Science and Technology Project, Old Executive Office Bldg., Room 428, Washington, DC 20500; (202) 456-7710.

## NASA picks 15,000-gate GaAs ASIC

The US National Aeronautics and Space Administration's Goddard Space Flight Center received functional prototypes last fall of a 15,000-gate chip for use in telemetry acquisition systems. The Vitesse Semiconductor Telemetry Frame Synchronizer was implemented in the GaAs Fury VSC15K gate array that is manufactured using the company's proprietary H-GaAs process technology. Anticipating superior performance and low power in the ASIC, NASA selected it over competing silicon bipolar and BiCMOS devices. The synchronizer boosts the upper limit of this type of system performance to 300 Mbps.

"Our requirements called for a high-performance ASIC that could integrate a lot of lower complexity ECL devices into one chip. We chose Vitesse's H-GaAs technology, not only because it offered the speed and integration we needed but because it allowed us to use traditional air cooling," said Jim Chesney, NASA's head of the

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*Send announcements of new microcomputer and microprocessor products to Managing Editor, IEEE Micro, PO Box 3014, Los Alamitos, CA 90720-1264.*

**Joe Hootman**

*University of North Dakota*

## DSP software, hardware

### I/O card operates in Windows

First to be released in a 200 Series of hardware products is the DI-200 data acquisition card designed to operate in the Windows and DOS programming environments. The 16-channel analog I/O card incorporates DSP-based technology, channel-by-channel programmability, and an 83-kHz burst sampling rate that minimizes channel skew. Promising 12-MIPS performance, the 16-bit DI-200 offers bipolar measurements from ±1.25V to ±10VFS (full scale) or ±10mV to ±10VFS and unipolar measurements from 0 to +1.25V, 0 to 10V ($A_v$ = 1) or 0 to +10mV, 0 to 10V ($A_v$ = 1,000). *Dataq Instruments; $795, delivery from stock.*

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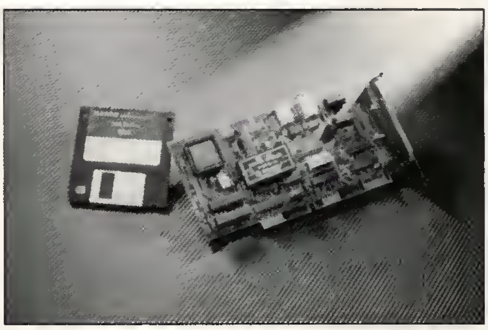

*Dataq Instruments' DI-200*

### Achieve 200-Mflops peak speeds

The MZ 7770 DSP VMEbus module features four interconnected TMS320C40 DSPs for interprocessor communication at 200-Mflops peak speeds. Each C40 with zero-wait-state SRAM holds three more 20-Mbyte/s communications ports that ease interconnections of C40s from multiple boards. Multiple MZ 7770s can be arranged in 3D-mesh, ring, or hypercube multiprocessor architectures. The 6U-size board suits a variety of signal and parallel processing applications and comes with an ANSI-compatible C compiler with a parallel processing runtime library. Additional software includes a C source-level debugger, Texas Instruments' pDSP XDS 510 in-circuit emulator with JTAG diagnostic support and the NOS operating system; an Ada compiler; and the SPOX, Helios, OS-9, and VxWorks operating systems. *Mizar; from $15,900.*

**Reader Service No. 11**

### Real-time VMEbus coprocessor

The 1.1-billion operations/s VMEbus DSP coprocessor called Hydra has added the Helios real-time operating system for development and execution of applications that run on large multiprocessor networks of up to 100 Hydras. Included with Helios are Unix-like PC- and Sun-based cross-development tools plus a real-time multitasking, multithreaded system that runs on the Hyrdra-based target system. The cross-development tools include ANSI C and Fortran compilers, TCP/IP networking, X Windows and Microsoft Windows graphics support, and Posix and BSD libraries.

Helios also supports interprocess communications and synchronization mechanisms including shared-memory locks and semaphores. Programmers can establish communications between multiple programs without specifying the physical connections by making a read or write call to a file descriptor. *Ariel; $3,500 (Helios), from $9,995 (Hydra).*

**Reader Service No. 12**

### TI introduces the C52, enhances C5X products

Promising high performance and low cost, Texas Instruments introduced its latest DSP chip and enhancements for its product line. Company spokesmen say the 16-bit, fixed-point TMS320C52

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DSP for telecommunications and other high-performance applications represents two to four times better performance than the popular C25. The 100-pin thin QFP device performs an instruction in 25, 35, or 50 ns for 40-MIPS execution at either 3.3V or 5V. Designed with a superset of the C25 memory and peripherals, the C52 features a 1K-RAM/4K-ROM configuration, a single serial port, and a single timer.

The C5X 16-bit DSP family also includes the C50, C51, and C53, each with an instruction set that is source-code compatible with C1X and C2X 16-bit DSPs. Enhancements include on-chip power management circuits that provide power consumption in active mode, 2.5-mA/MIPS at 5V and 1.5-mA/MIPS at 3.3V, as well as two power-down modes. *Texas Instruments; $15.95 (1,000s) and $10 (100,000s); C5X volume production 2Q93.*

**Reader Service No. 13**

### Software release supports Windows

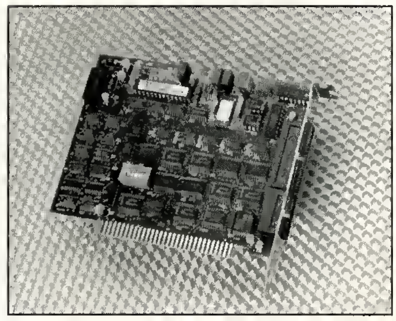
Hypersignal-Windows RT-3 is an integrated signal processing software package of data acquisition, real-time DSP, graphical analysis, visually programmed algorithm development, and DSP development tools, all of which work together. The just-released Version 1.30 features extended snap-in digital filtering, enhanced graphing capabilities such as waveform overlay and 2D and 3D frequency displays, a larger function library with user-written C-compiled blocks, and high-accuracy frequency markers on the spectrum analyzer. According to the manufacturer, the Hypersignal-Windows RT-3 package supports 20 DSP/acquisition boards for real-time instruments. *Hyperception.*

**Reader Service No. 14**

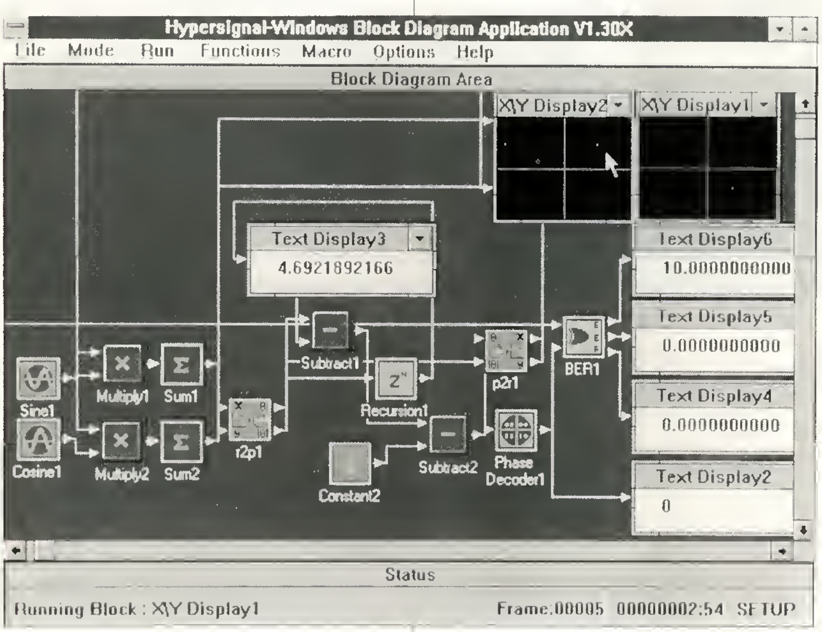
### Board consumes 1W power

A 5.3-inch data acquisition board that uses 1 watt of power supports remote and portable applications with 16 single-ended or eight differential analog input channels (12-bit resolution). The PCI-20377W-1 features a 45-kHz throughput rate; programmable gains of 1, 10, 100, and 200; 16 protected digital I/O channels; and a rate generator. A 16-word FIFO buffer ensures continuous data flow to the host when the host is temporarily unavailable. All user-selectable configuration features such as gain, signal range, and single-ended/differential modes are software controlled. The board includes Master Link software libraries for DOS and Windows environments and the Syscheck system assurance utility. *Intelligent Instrumentation; $495.*

**Reader Service No. 15**



*Intelligent Instrumentation's PCI-20377W-1*




*Hyperception's Hypersignal-Windows*

## Software

### RS/6000 development tools

Now running on IBM RISC System/6000 workstations are Intel's i960 and 8086 microprocessor development tools: the ANSI C cross compiler, macro cross-assembler, and Xray debugger. Xray debugs optimized C code, supports instruction-set simulation, and features the X Windows System Motif interface. The optimizing C compilers comply with the ANSI C standard and accept programs written in the original C language as defined by Kernighan and Ritchie. The C++ compilers comply with Version 2.1 of the AT&T specification. *Microtec Research; from $4,300.*

**Reader Service No. 16**

### Desktop Design Architect

Design Architect PCX lets users run it and Falcon Framework under X Windows while the actual application takes advantage of computer power elsewhere on the network. The package supports schematic entry, remote simu-

lation and synthesis, and QuickSim II in X configurations for graphical display on an X terminal. The company promises to qualify and fully support Sparc workstations with Open Windows 3, HP-PA workstations with HP/UX 9.0, and a variety of other X terminal configurations. *Mentor Graphics; $7,500 per user (3-6 user configurations).*

**Reader Service No. 17**

### Windows I-CASE tool

Version 5.0 of Visible Analyst Workbench I-CASE supports the Microsoft Windows operating environment. The integrated tool set features forward- and reverse-engineering capabilities such as SDM, Yourdon Structured Method, and Information Engineering. Users can generate SQL database schemas, Cobol source code, and C source code from designs developed in the system. Other enhancements include multipage document support, ease-of-use, model navigation improvements, control bar support, repository data access, and text editing. Version 5.0 is upward-compatible with Versions 4.2 and 4.3. *Visible Systems; from $1,895.*

**Reader Service No. 18**

### ASCII, math packages

Turbo Spring-Stat Text Editor II, an ASCII data file editor, supports 64K windows of different files as free memory allows, an optional mouse, and a clipboard; it does not require Windows to operate. Each window with scroll bar is movable and resizable, letting users cut and paste within and between files. Text Editor II requires MS-DOS 2.0 or higher, a 512-Kbyte RAM, and CGA/EGA/VGA or compatible graphics capability.

The Equator II menu-driven mathematical equation storage, evaluation, and plotting system lets IBM users save equations, document variables and parameters used, and evaluate expressions to create tables, graphs, or disk files. Equator II users can also import data files from other sources for plotting. Results may be viewed either on the screen or sent to an Epson or compatible dot matrix printer, an HP LaserJet, or an HPGL plotter. Equator II requires MS-DOS 2.1 or higher, CGA/EGA/VGA graphics capability, 512 Kbytes of RAM, and two 720-Kbyte floppy drives. *Dynacomp: $39.95 (Text Editor II), $79.95 (Equator II); 20-percent discount if order accompanied by this page.*

**Reader Service No. 19**

### Simulation models for PLDs

Behavioral models for the Altera Multiple Array Matrix (MAX) 7000 programmable logic devices have been added to the Logic Modeling Smart Model Library. This 6,500-component library interfaces with MAX+Plus II development tools for accurate modeling of functional and timing delays in an Altera-compiled PLD. Smart Models run on Verilog, QuickSim II, ViewSim, CADAT, HiLo, and VHDL simulators on most Unix workstations. *Altera Corporation and Logic Modeling; shipped with subscriptions/updates (new models), $10,000 per workstation (full library license).*

**Reader Service No. 20**

### Visual Basic gains database manager

Agility/VB lets Visual Basic programmers create database applications using custom controls without writing a line of code. The package includes grid, text, button, and picture controls, and a set of commands that provides program control over database applications. A View Editor tool specifies relationships between multiple, different-format databases in a view so programmers can see them as a single flat file while maintaining all relations and indexes. An Agile Assistant programming aid helps users manage database-related programming tasks.

Agility/VB supports dBase and text file formats and provides its own database for variable-structure and variable-length data storage. The manager requires Microsoft Windows 3.X, Visual Basic 1.X or higher, and an 80286 processor; 2 Mbytes of RAM is recommended. *Apex Software Corporation; $189.*

**Reader Service No. 21**

### LabWindows adds C++ libraries

LabWindows for MS-DOS Version 2.2.1 instrumentation software now includes stand-alone libraries for the Borland C++ and Turbo C++ compilers and Microsoft Visual Basic for DOS (VBDOS) compiler. Version 2.2.1 offers float data type DSP Analysis Library, new cursor functions, DPMI memory manager capabilities, and a library for performing DOS file and directory commands directly from LabWindows.

The C++ libraries let users access the Borland compiler and linker from within LabWindows to create executable programs or add LabWindows libraries to the Borland Interactive Development Environment for program development. Each of the libraries has a Borland-compatible help file that users can load into the IDE for on-line help. Basic programmers in VBDOS can incorporate LabWindows instrumentation functionality into their applications, access the VBDOS compiler from within LabWindows, or load the LabWindows libraries into VBDOS as an external Quick Library. *National Instruments; free upgrades to 2.2 users, $195 for upgrades from previous versions.*

**Reader Service No. 22**

### EDI translator/manager

The Electronic Data Interchange EDI*Transit translation and management system works in both Unix and MS-DOS environments. The program reduces EDI document processing time and features mapping capability, translation of all key standards, task scheduling, and functional acknowledgment tracing. In addition, predefined communication scripts allow easy access to the company's EDI*Express Service. *GE Information Services.*

**Reader Service No. 23**

### Process control enhancements

ExpressLite, a recent release of the Express event management and control system for process control and factory automation applications, offers enhanced graphics, communications options, I/O drivers called Opto-22 Optomux and Modicon V984, and an historical trend-recording feature. Included with ExpressLite is a demonstration application supplied with source code that users can run, modify, or replace with a custom application. ExpressLite supports all Express functions but no actual I/O drivers, up to 256 simulated I/O points, one terminal, and one printer. *Forth, Inc.; $195 (ExpressLite evaluation version), $6,875 (Express)*

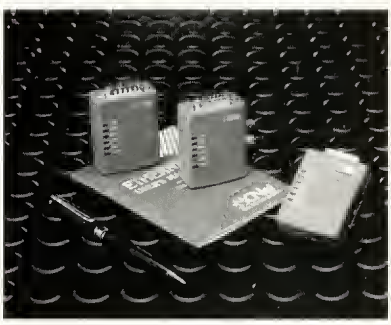
***Reader Service No. 24***

## Communication devices, software

### Transceivers fit in vest pockets

The 2-oz. CN815E and CN825E transceivers offer an upgrade path from coaxial cable. The CN815E AUI-to-10BaseT interface and CN825E coax-to-FOIRL (fiber optical interrepeater link) converter support PC, Macintosh, and Sparc Station platforms and are compliant with 10BaseT and fiber optic Ethernet standards. Each 2.28 × 1.79 × 0.9-inch transceiver includes automatic polarity correction and status LEDs for power, transmit, receive, collision, link, and jabber (SQE) signal display. *CNet Technology; $129 (CN815E), $399 (CN825E).*

***Reader Service No. 25***



*CNet Technology's transceivers*

### Managing tolls and traffic

An IVHS platform system for electronic toll collection reduces traffic congestion, fuel consumption, and auto emissions by allowing motorists to travel nonstop through toll lanes. According to the manufacturer, the New Hampshire State Police tested the patented radio frequency identification technology at speeds in excess of 90 mph.

The microprocessor-based read-write device improves on the read-only process that uses either barcode tags or radio-reflective tags to read a passing vehicle's ID. Read-write allows information, such as the entry point of a turnpike for later toll calculation, to be written onto an intelligent transponder placed in a vehicle. Like a postage meter, the transponder is electronically charged with a value, and that value is reduced each time the car passes through a toll lane. An LCD display and audio alarm on the device give the motorist real-time information on the remaining amount. *Dover Electronics and At/Comm.*

***Reader Service No. 26***

### Create RS-485 networks with 496 nodes

A wiring concentrator for RS-422 and RS-485 networks lets users create RS-485 networks with up to 496 nodes and mix RS-422 and RS-485 systems on the same network. Model 290 uses an RS-232 master port and 16 slave ports that are independently programmable to either type of port. If each port is configured for RS-485 and considered a pseudo master port, users can expand the network to 496 nodes. Since separate driver/receiver circuits drive each of the 16 ports, a port failure is isolated from all other ports.

The 17W × 10D × 1.7H-in., aluminum-enclosed Model 290 can be changed from a standard desktop configuration to wall-mount or conventional 19-in. rack mounting. *Telebyte Technology; $725, delivery 2-4 weeks ARO.*

***Reader Service No. 27***

### Apple supports SNMP

Apple Talk and TCP/IP network software now incorporate the Simple Network Management Protocol. System administrators can manage Macintosh personal computers on global networks using SNMP management consoles. Apple Talk Connection for Macintosh and TCP/IP Connection for Macintosh also provide a new System 7 service called the SNMP Manager that supports Watch Tower from Inter Con Systems Corp. and LAN Surveyor from Neon Software Inc. *Apple Computer; from $39 (single-user Apple Talk Connection), from $59 (single-user TCP/IP Connection).*

***Reader Service No. 28***

### Modem communicates via memory-mapped scheme

The credit card-size, 2,400-baud Palm Modem card supports subnotebook and palmtop computers, communicating via a memory-mapped scheme, transmitting faxes, and running over 15 hours on two AA batteries. This PCMCIA Version 2.0 modem serves 8-bit processors such as the V20, Hopper Chip for the HP95LX, PC/Chip, V30, and the Zeo palmtop CPU. For the HP95LX, the modem contains a software interface compliant in format with Hewlett-Packard's system manager software. All of the software required to run the Palm Modem in the HP95LX is supplied on the card. *New Media Corporation; $259 (HP95LX version).*

***Reader Service No. 29***

### Reader Interest Survey

Indicate your interest in this department by circling the appropriate number on the Reader Service Card.

Low 189 Medium 190 High 191

# Product Summary

***Joe Hootman***
*University of North Dakota*

| Manufacturer | Model | Comments | R.S.# |
|---|---|---|---|
| **Boards** | | | |
| Allen Systems | MP-11 SBC | Single-board computer designed for process control applications is based on the 8-bit 68HC11F1 microcontroller. The 4.5×5.5-in. MP-11 offers 16-MHz operation, power/ground planes for noise minimization, and a processor supervisory circuit. An expansion connector supports custom user circuitry or an optional A/D and D/A daughterboard. *$100 each (bare board/manual), $300 each (assembled/tested board); volume pricing available.* | 80 |
| Emulation Technology | HP-P5-PGA 14-UI preprocessor | Passive board including configuration software provides a timing analysis-only interface between Intel's Pentium microprocessor and most Hewlett-Packard logic analyzers. The preprocessor allows designers to make quick connections to a Pentium under test. The interface comes with built-in termination resistors. *$995 each; 10 days ARO.* | 81 |
| Gespac | GESMPU-46 SBC | Single-height Eurocard features a 20-MHz Cyrix 486 CPU chip, 486-code compatibility, two serial ports, and one bidirectional parallel printer port. Pairing with the GESVGA-1 enhanced VGA card produces AT compatibility in a form factor small enough for embedded industrial applications. *$1,795 each; available from stock.* | 82 |
| MNC International | MNC 1152 SBC | Single-board computer based on the 25-MHz Cyrix 486SLC processor promises a Landmark 2.0 CPU rating of 78 MHz. The passive backplane includes an SVGA CRT adapter, flat-panel (LCD and plasma) adapter, 1-Mbyte Flash memory, and clock/calendar. *$695 each, evaluation units; volume pricing available.* | 83 |
| **Chips** | | | |
| Cirrus Logic | CL-GD6440 LCD controller | Super VGA LCD device connects to a 32-bit local bus and a 32-bit video memory interface, offering desktop graphics capabilities in notebook computers. Two 256K×16 DRAMs provide 1 Mbyte of video memory, and integrated GUI assist functions support Microsoft Windows. The 208-pin QFP supports dual-scan color STN panels. *$40 each (5,000s).* | 84 |
| Mitsubishi Electronic Device Group | M38203M4/223M4/254M6 MCUs | Eight-bit microcontrollers with LCD controller and driver use 2.7V power. The ROM-based devices operate at up to 2 MHz with 2-µs minimum instruction executions and 8-mW typical power dissipation. *$4.85 to $6.75 each (10,000s).* | 85 |

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# IEEE MICRO

# Editorial Calendar

## FEBRUARY 1993

*Automotive/traffic microelectronics*

- Worldwide developments in microelectronics for traffic and driving assistance
- Improving traffic safety with electronics
- Latest developments from Japan, the European Prometheus, and US IVHS programs

**Ad closing date: January 2**

## AUGUST 1993

*Multitheme issue*

- Multiprocessing
- Optical and biological computing
- Microcomputing to aid the handicapped
- Systems design
- DSP-based tools

**Ad closing date: July 1**

## APRIL 1993

*Advanced packaging and interconnection technology*

- Critical packaging trends and issues
- Substrate and package technologies—for example, flexible, glass, or diamond substrates; few-chip or 3D packaging
- Attachment, bonding, and connection technologies, including fine-pitch surface mount, laser applications, known-good die, and interconnection trade-off analysis

**Ad closing date: March 1**

## OCTOBER 1993

*Far East issue*

- Microcomputer and RAM technology
- High-performance parallel computer research
- Current TRON Project offerings, Japan's standard computer system
- Singapore technology update

**Ad closing date: September 1**

## JUNE 1993

*Hot Chips IV*

- This extremely popular issue presents the latest developments in microprocessor and chip technology used to construct high-performance workstations and systems as presented at the annual IEEE Computer Society TCMM-sponsored symposium

**Ad closing date: May 1**

## DECEMBER 1993

*Special standards issue*

- Buses and interconnections
- Processor architectures
- Current activities: IEEE and other standards bodies
- How standards can help designers

**Ad closing date: November 1**

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